8. HIGH-STRENGTH STEELS

A. Modeling of High-Strain-Rate Deformation of Steel Structures

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Objective

- Develop numerical modeling guidelines to realistically assess the influence that the properties of strain-rate-dependent materials exert in crashworthiness computations.

Approach

- Model dynamic loading problems using diverse combinations of modeling approaches (submodels) that are essential in describing strain rate sensitivity in computational simulations. Submodels examined include finite-element method (FEM) formulations, constitutive materials models, material properties under different strain rates and loading conditions, contact conditions, etc, as well as material property changes caused by component processing.

Accomplishments

- Investigated effects of stress transients for high-strength steel (HSS) and their effects on peak impact force.
- Developed experimental setup for new crashworthiness characterization test based on parallel-plates buckling (test under way at the University of Dayton Research Institute).
- Developed program for analysis of history of strain rate calculations.
- Analyzed history of strain rates in unsymmetric crushing.
- Determined modeling effects on strain rate history in unsymmetric crushing.
- Modeled effects of stress and strain transients on initial impact force.
- Developed framework for modeling stress transients.
- Reviewed literature on Bake Hardening (BH) and proposed a model for FEM analysis.
- Reviewed literature on fracture and damage in impact of HSS.

Future Direction

- Develop new constitutive models for HSS to account for strain rate history and transients.
- Develop new constitutive models for modeling of damage and tearing of HSS during impact.
- Conduct and analyze crush experiments (parallel-plates and tube crush).
- Develop experimental guidelines based on the two tests above.
- Determine optimal FEM formulations for modeling of crushing of rectangular tubes.
- Develop experimental program for crushing of rectangular tubes.
- Develop modeling guidelines rectangular tubes.

Introduction

The objective of the project is to develop numerical modeling guidelines for strain-rate-dependent materials in crashworthiness computations. The scope of the project is to study specific structural problems in automotive impact, develop new experimental and analytical techniques for characterization of strain rate sensitivity of HSS and modeling of complex strain and strain rate histories. The dynamic loading problems are modeled using diverse combinations of modeling approaches (submodels) that are essential in describing strain rate sensitivity in computational simulations. Submodels to be examined include finite-element formulations, constitutive materials models, contact conditions, etc. The trends, influences, and direct effects of employed modeling techniques will be identified and documented. The relative significance of employed sub-models is established, particularly in relation to the strain rate effect resulting from the material constitutive models.

The research project is conducted as a team effort between the ORNL and the Auto/Steel Partnership Strain Rate Characterization Group.

FY 2003 Work Summary

Several important research milestones were completed during FY 2003. First, we investigated modeling of impact of symmetric HSS structures under unsymmetric crushing and developed computer programs for analysis of strain rate histories. The experimental results from drop tower tests were used for comparison with models. The material models were developed based on coupon-level experiments in different experimental apparatus and were used for tube crush simulations. The differences in characteristic material response as a function of strain rate between different steel types were investigated with an objective to develop a unifying approach for HSS constitutive material modeling. The material modeling effects such as strain rate formulations, element formulations, mesh density, and stress transients as function of strain rates and strain rate histories were investigated for their effect on the simulated impact response and compared with experimental results. Modeling guidelines were developed in terms of modifications of constitutive material models and analysis options that yield best agreement with experiments and have sound physical foundation. BH has been identified as an important strengthening mechanism that will be exploited in future car designs with new HSS. Therefore, review of BH literature has been conducted, and a new model has been proposed for incorporation of BH effect in impact simulations.

The new research findings were presented at the 2003 SAE World Congress[1] and United States Congress on Computational Mechanics.[2] The developed models, experimental data and presentations are available at the project Web site: http://www-cms.ornl.gov/asp. Please contact Srdan Simunovic, simunovcs@ornl.gov for access.

In the following sections, significant research findings during FY 2003 will be described and discussed in the context of their relevance for development of more accurate models for impact simulations.

Strain Rate Sensitivity Modeling of HSS for Unsymmetric Crushing

Strain rate sensitivity of HSS has been mostly analyzed in the context of symmetric deformation of axisymmetric structures. The symmetric axial crushing of tubular specimens has been used as a basic model for crashworthiness analysis in many analytical, semianalytical, and numerical models.[3] The research in the previous year of the project has investigated the history of strain rates during the axisymmetric impact simulations. We have investigated the effects of modeling approaches on strain rate history and the consequence of the modeling assumptions on the required experimental program to support the modeling. The research established for the first time the relation between the FEM modeling approaches and the strain rate history calculations at the level of computational time step. This relation is important because all the strain rate calculations in constitutive models and effects occur at this very fine time scale that is usually several orders of magnitude smaller than the time scale that is usually used to analyze the structural response.

Strain rate history in unsymmetric crush is more difficult to analyze because we cannot make simplifying assumptions of symmetry. For example, in simulation of axially symmetric crushing of circular tubes, symmetry reduces the dimensionality in the problem so that it is sufficient to analyze only a longitudinal strip of a circular tube. When the circular tube crushes in unsymmetric mode, such simplification is not possible. The consequence is that we now have to analyze large areas of the structure, both in longitudinal and hoop direction, and investigate the three-dimensional features of rate history. To enable the strain history analysis, we have developed a computer program that extracts the data from the simulation during its execution, processes it, and stores the process data in a compressed form. Such an approach allows us to reduce the data size by several orders of magnitude and still preserve the needed information. The developed program can also be used in general FEM impact simulation using LS-DYNA3D[4] for detailed investigation of important structural areas that are experiencing complex strain rate histories.

Tube Crush Experiments in Drop Tower

In this project, HSS materials HSLA350 and DP600 were selected for drop tower experiments to investigate the accuracy of the constitutive models based on a piecewise linear plasticity model and various modeling approaches. A test for HSLA350 steel configuration and the final deformed shape are shown in Figures 1 and 2. Force, accelerations, and high-speed photographs are recorded during the experiment.

Force-time traces for two HSLA350 specimens are shown in Figure 3.

The force-time diagram shows the characteristic peak followed by the force plateau associated with progressive tube folding.

Figure 1. Test configuration for HSLA350.

Figure 2. HSLA350 tube at the end of experiment.

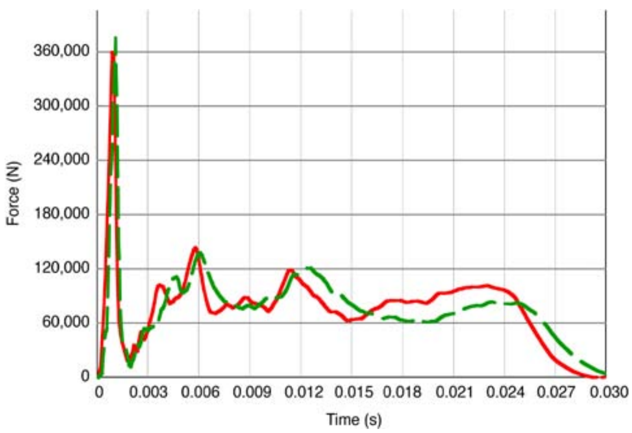


Figure 3. Force history for HSLA350 tubes.

The HSLA350 tubes deformed in an unsymmetric, triangular pattern. The anti-symmetric modes are principal mechanisms of deformation for the tube dimensions and the ranges of imperfections considered.

Impact Simulations and Strain Rate History

Drop tower experiments were simulated using the strain rate sensitive material models described in the previous section. Due to the collapse mode (Figure 4), it is necessary to select a relatively large representative patch of elements to analyze. The selected domain for strain rate history analysis is marked in lighter color in Figure 5. This patch of elements contains a corner of the polygonal collapse pattern for the rate

Figure 4. Unsymmetric axial collapse mode of circular tube.

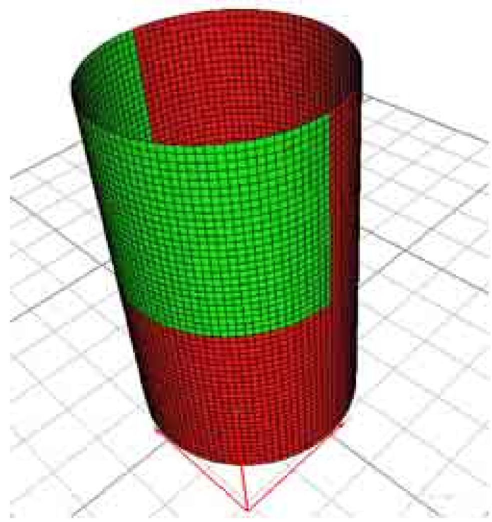


Figure 5. Elements selected for strain rate history analysis.

history. The strain and strain rate history is analyzed for different modeling approaches, and the results were used for determining guidelines for modeling approaches to automotive impact simulations.

Figures 6 and 7 show characteristic results from the simulations. In these figures, the selected domain is unwrapped into a flat surface and strain rates for different time instances are plotted normal to it. Figures depict the sequence of strain rate distributions for increasing time steps. The impact occurs at the NW side of the mesh in the

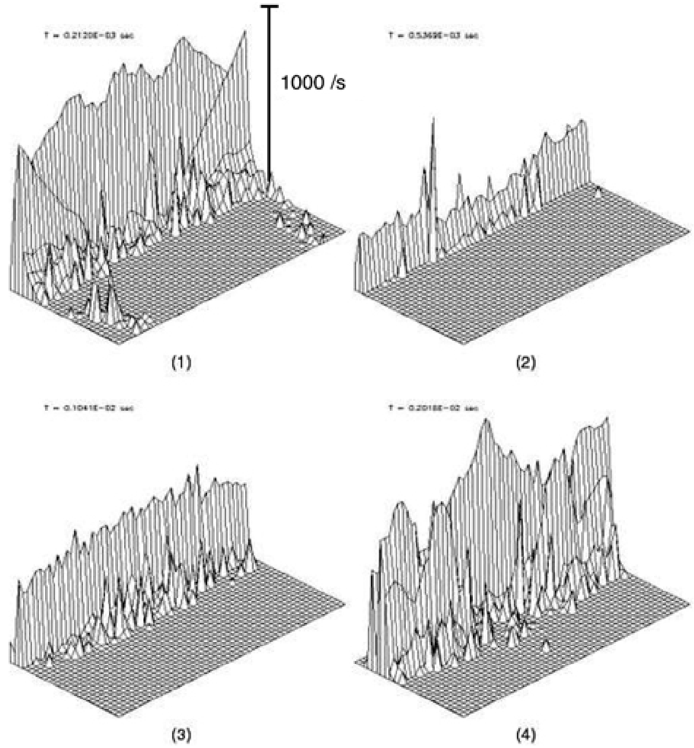


Figure 6. Strain rate history for material model based on total strain rate.

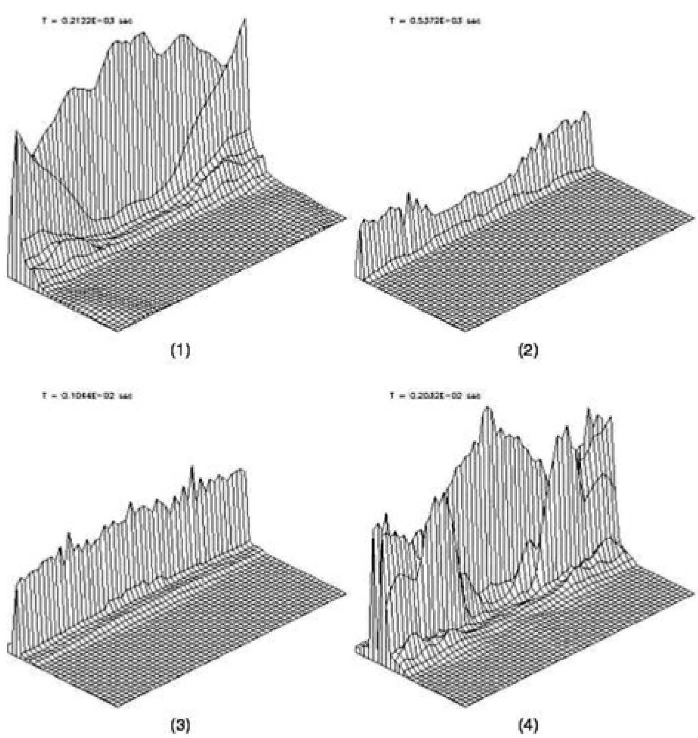


Figure 7. Strain rate history for material model based on plastic strain rate.

image, and rates propagate with time along the tube length, that is, in the SE direction. The white arrow in the figure denotes strain rate magnitude of 1000/s. The material model employed for the analysis is based on total strain rate formulation. The strain rate history in this case exhibits significant oscillations. The elements remain in an elastic state for prolonged periods of time, and then the plastic deformation occurs in bursts that have a very high strain rate that regularly exceed 10000/s.

On the other hand, when the strain rate sensitivity is based on plastic strain rate, the rate history is much smoother with gradual temporal and spatial transitions as can be seen in Figure 7.

In this case, the strain rates rarely reach rates of 1000/s and are well within the range of the available experimental data. The significant implication for modeling is that the material models where strain rate sensitivity is based on total strain rate do not take the advantage of the material data that were gathered with significant expense. When the total rate formulation is used for modeling rate sensitivity, much simpler models can be used that will yield essentially same results. The importance of the cut-off strain rate is also exacerbated because the resulting stresses for the rates exceeding the maximum available rate in the model will be scaled back to those provided for the maximum rate. A discussion about the physical aspects of different modeling approaches is beyond the scope of this document.

A journal publication is under preparation and will be available on the project Web site. Further analysis and discussion on the physical and modeling aspects of the problem are subjects of the journal publication that is in preparation.

The Effect of Stress Transients on Impact Peak Force

Impact experiments with tubes have shown a pronounced force peak for some types of steels that cannot be accounted for with existing strain rate dependent constitutive models. These same steels in coupon-level strain rate experiments show pronounced stress transients with increasing strain rate. These transients are usually discarded in development of constitutive models because presence of softening regions in stress-strain relation brings about significant problems with FEM formulation and uniqueness of the results. However, when strain rate sensitivity is present in the model, and when it is evaluated in certain fashion, these problems are to a large extent eliminated, and stress transients during initial impact and strain rate variations can be taken into account. Figure 8 shows modified stress-strain data where stress transients based on experimental data were added from rate 0.1/s.

When this model is used for simulation of tube crush, an excellent agreement with the initial force peak is found. The comparison of the simulation and the model is shown in Figure 9.

The softening regions of the stress-strain curves do not severely affect the uniqueness of the solution if the material model is based on plastic strain rate. Together with strain rate sensitivity this introduces a characteristic length scale, stabilizes the model evaluation, and alleviates spurious mesh sensitivity.

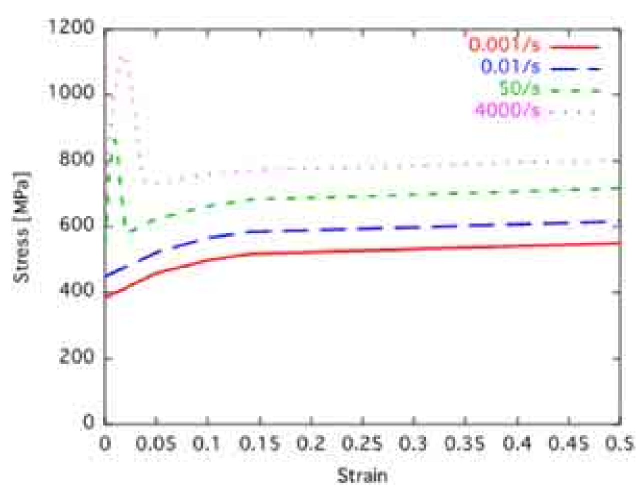


Figure 8. Modified HSLA constitutive model with stress transients.

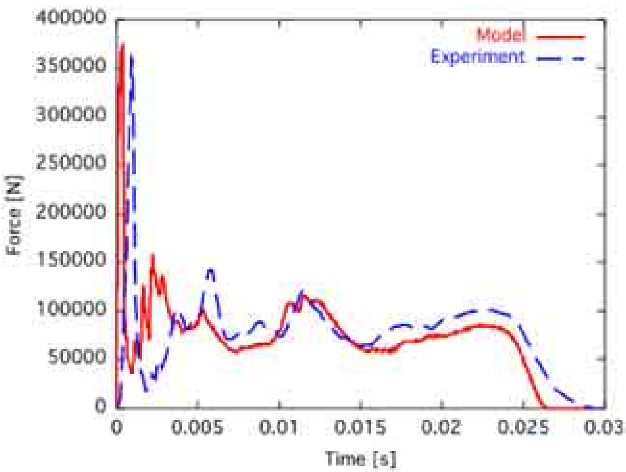


Figure 9. Modified HSLA constitutive model with stress transients.

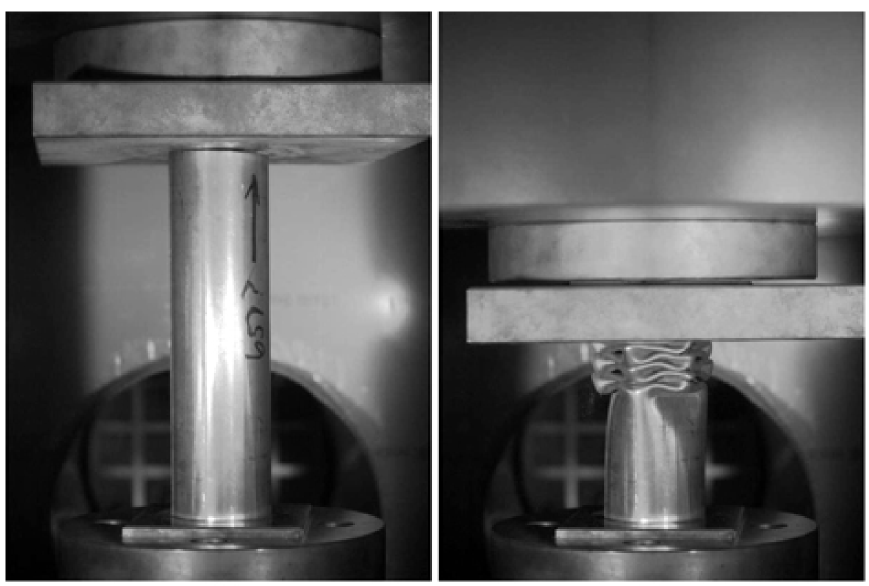
The stress transients are dependent on strain rate history, and the above treatment is just a first-order approximation of the phenomena. A more fundamental approach is under development that will result in extension of the current strain rate dependent model to account for strain rate history. A journal publication is under preparation to further elaborate on the project developments.

Tube Crushing using Controlled Displacement Equipment

Preliminary tube crush experiments were conducted at the ORNL Test Machine for Automotive Crashworthiness (TMAC) on equipment described in the overall report (7.C). TMAC provides tightly controlled impact conditions that are used for generation of high-quality data for verification and development of new material models and FEM formulations. Tubes made of DP590 and TRIP590 steels were crushed at various speeds. Imperfection was introduced by making the top edge of the tube at a prescribed angle with the actuator, as shown in Figure 10.

The experiments were simulated using an isotropic plasticity and strain rate dependency described by a piecewise linear plasticity model. The simulation was conducted for dual-phase (DP) steel tube under constant crush velocity of the actuator of 0.6 m/s. Tube configuration at 200 ms is shown in Figure 11. The colors in the figure denote magnitudes of plastic strain in the finite elements.

The comparison of deformation features (displacements and curvatures) between the



(1) (2)

Figure 10. TMAC tube test.

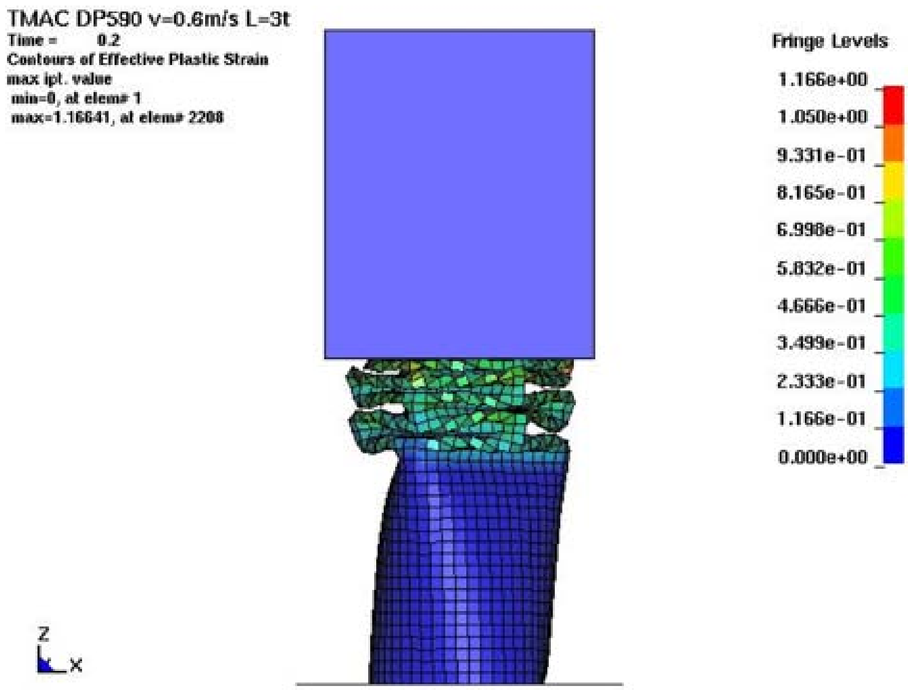


Figure 11. Plastic strain of DP tube at 0.2°s; crush velocity 0.6 m/s.

models and experiments is still ongoing, but the global data can be readily compared. Figure 12 shows the comparison between the experiment and the model. Data have not been filtered.

The model correctly predicts the initial stiffness of the tube, but it fails to achieve experimental peak. The origins of the peak impact force have so far been difficult to isolate because of the coupling between

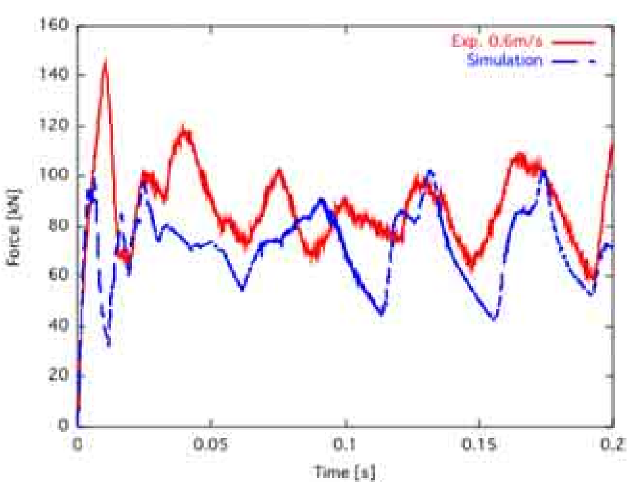


Figure 12. DP tube crush force; crush velocity 0.6 m/s.

the test specimen and testing equipment and inertia of the measurement devices.[5,6] The current results indicate that the peak value is not an artifact of testing but that such force is really experienced by the specimen. The actuator rigidity and inertia together with the measurements from the load washer at different constant loading velocities imply that the origin of the peak force is in the material behavior. The material model would, therefore, have to be modified to include strain rate history effects. Strain rate history effects had been investigated in the past,[7,8] but they have not yet found a wide acceptance in the engineering practice. The experimental data from TMAC can provide necessary information for such material model modifications and further improve predictive capability of the FEM.

Conclusions

The current project concentrates on investigation of different FEM modeling approaches for modeling of impact in HSS structures. The research is performed in collaboration with experimental program on characterization of HSS under impact. The modeling is also used for development of new high strain rate material and structural characterization tests. The results of the project are used for development of more accurate modeling approaches for automotive design. The research results are also applicable in high strain rate forming operations.

Future Work

The future work on the project will focus on four topics:

1. Support of the strain rate experiments on coupon and component level.
2. Development and validation of material models and modeling techniques.
3. Modeling of HSS rectangular tubes.
4. Development of models and experiments for damage and fracture of HSS in crash.

The remaining most important aspects to address from the modeling of HSS crashworthiness are the methods to model the crush of tubes with rectangular (polygonal) cross section, modeling of damage that the HSS experiences during the deformation, and incorporation of processing into the models.

Acknowledgments

The research was performed at the Oak Ridge National Laboratory (ORNL), which is managed by UT-Battelle, LLC for the U.S. Department of Energy under contract DE-AC05-00OR22725. The drop tower tests were performed at the Vehicle Safety and Crashworthiness Laboratory, General Motors Corporation, Milford Proving Grounds. The tubes for the TMAC experiments were donated by the U.S. Steel Corporation. The support of Auto/Steel Partnership Strain Rate Characterization Team is acknowledged.

Contact

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B. Enhanced Forming Limits

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Contract No.: DE-FC05-020R22910

Objective

- Convert the research results of the Auto/Steel Partnership (A/SP) Enhanced-Forming-Limit Diagram (EFLD) Project Team into an application methodology usable in press shops, and disseminate the resulting application methodology to steel suppliers and users to facilitate the manufacture of lightweight steel vehicles.

Approach

- Study the final research report by the EFLD Project Team to provide the technical foundation for an application methodology applicable to press shop functions.
- Create the application methodology.
- Validate the new application methodology with press shop case studies.
- Prepare reports and materials necessary for training seminars and conduct the seminars.

Accomplishments

- Established a Bead Correction Factor (BCF) to convert from bending and unbending strains generated during sheet metal deformation through draw beads or over sharp tool radii to corrected strains suitable for plotting on existing forming-limit curves (FLCs).
- Published a technology report documenting the creation of the BCF, procedures for using the BCF, detailed computational work sheets for five case studies, and limitations for press shop application on the A/SP open Web site.

- Published a training manual for press shop implementation on the open A/S-P Web site. The manual combined key portions of the technology report with additional instructions on how to use the BCF.
- Conducted seven training seminars for steel suppliers, steel users, tool and die builders, and formability researchers.

Future Direction

- Completed all work on this project.

Introduction

For decades the FLC and circle grid analysis (CGA) have defined the limits of sheet metal deformation from die tryout through production in real world manufacturing and now have been applied to virtual (computer simulation) manufacturing. However, several important areas of the stamping were excluded from these analyses. Sheet metal deformed by bending and unbending through draw beads or over tool radii with radius-to-sheet thickness ratios less than 5 had strain gradients through the sheet thickness and underwent large amounts of strain reversal. The FLC could not be used for forming severity assessment for these modes of deformation. However, severity analyses of these deformation modes become especially important for utilizing high-strength steels, thickness reductions, and other weight reduction opportunities.

The A/SP conducted and successfully completed an extensive research program entitled "Enhanced Forming Limit Curves" (EFLC) to study the forming severity of bending and unbending sheet steel. Their complete research report and additional data spreadsheets can be downloaded from their open Web site www.a-sp.org. The last phase of this program—transformation of the research results into usable press shop procedures—was completed in 2003.

Project Details

The project to develop press shop procedures was conducted as a consecutive series of five tasks. Completion of all tasks meant original equipment manufacturers (OEMs), steel companies, tool and die shops, and others involved in forming sheet metal were capable of implementing a simple press shop floor severity assessment for the bending and unbending forming modes.

Task 1: Convert research results to an application methodology suitable for press shop implementation.

The research program utilized measurement of FLCs before and after bending and unbending deformation. The height of the FLC after bending and unbending was higher than the FLC of the as-received steel. Thus the name of the project team was EFLC. While an excellent research tool, increasing the allowable amount of stretch before failure by cold working the metal through a draw bead would be difficult to explain and even harder to implement in the press shop.

However, the research showed that only 40% of the deformation going through draw beads actually affected the stretchability of the sheet steel. Rather than creating many different EFLCs for different amounts of bending and unbending strain within a given stamping, a BCF was created that corrected (reduced) the level of the measured strain by 60% before plotting the data on the FLC (Figure 1).

The BCF is proportional to the thickness strain created by the draw bead and/or tool radius. Because strain correction factors already were utilized by many stampers to correct strain severity readings measured on the outer fiber plane of a single bend, the BCF was deemed a reasonable and suitable tool for the press shop.

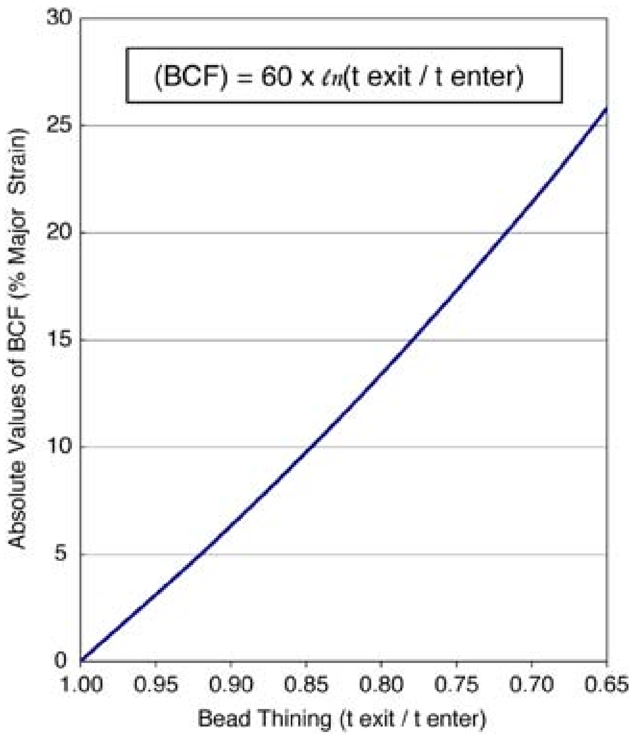

Figure 1. The BCF shown as a function of the thinning through the draw bead.

The computed BCF (a negative number) is added to the measured major strain and then plotted on the FLC as shown in Figure 2.

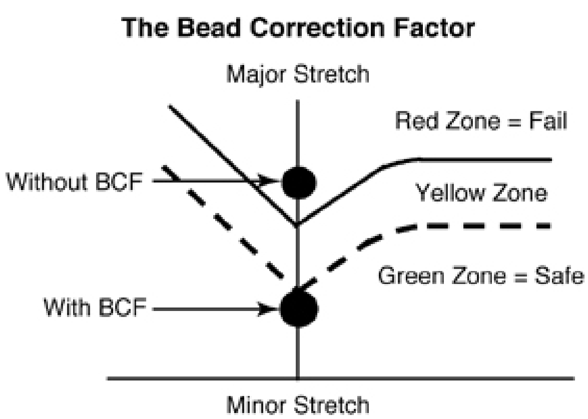

Figure 2. Forming-limit diagram (FLD) showing the effect of the BCF in lowering forming severity.

Task 2: Conduct press shop trials.

Task 2 was a very important milestone for completion of this project. The BCF procedure developed in Task 1 was applied to actual stampings in various press shop environments, including die build, die buyoff, and production. The first goal was to validate the analysis procedure on production stampings instead of the special test pieces created during the research phase. The second goal was to acquire case studies useful for the subsequent training phase of the project. From the group of stampings studied, five were selected for inclusion in the formal reports because of their special benefit for validation and training.

Case study 1 was a hood outer measured at final die buyoff. Figure 3 shows location C that had not undergone bending and unbending through the draw bead and therefore was analyzed using the traditional FLC. The strain at location C was only 35 strain percent major strain (direction of arrow) and 0 strain percent minor strain (perpendicular to arrow). However, this strain was located above the FLC line, and failure was predicted.

Figure 3 shows that location B of the stamping that had undergone bending and unbending through the draw bead, but had not torn.

The strain at location B was 47 strain percent major strain and 0 strain percent minor strain, which had a major strain one-third higher than the tear at location C. When the BCF was applied to location B, the

Figure 3. Hood outer stamping highlighting two measurement areas.

major strain was reduced from 47 strain percent to 24 strain percent. The severity was now in the green zone. This change in severity is illustrated in Figure 2.

Case study 2 was a fender at press show. The day before the show the fender passed all tests and evaluations. On press show day, however, the fender split (Figure 4) with engineers and die buyoff staff present.

The measured major strain was 58 strain percent, which was well above the 35 strain percent strain allowed by the FLC. Subtracting the computed BCF of 19 strain percent, a corrected major strain of 39 strain percent was obtained. Even after the BCF was applied, the strain was still above the 35 strain percent allowed by the FLC, and failure was predicted. The resultant tear indicates that the BCF is a reasonable compensation factor and will correctly predict failures in steel pulled through draw beads.

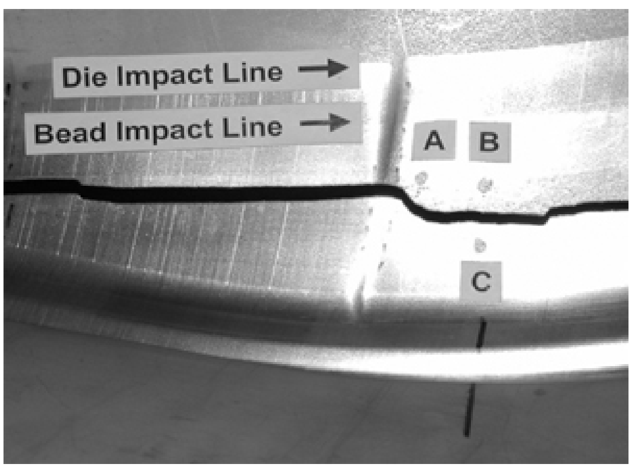

Figure 4. Fender showing severe split in metal pulled through a draw bead.

Case study 4 was a hood outer panel that had been in production more than a year (Figure 5).

When production was started on this hood, the major strain was 51 strain percent and well above the 36 strain percent allowed by the FLC. However, no tears had been encountered during die tryout or die buyoff. The company was aware of the EFLC project and therefore made the decision to release the tooling for production. During the year

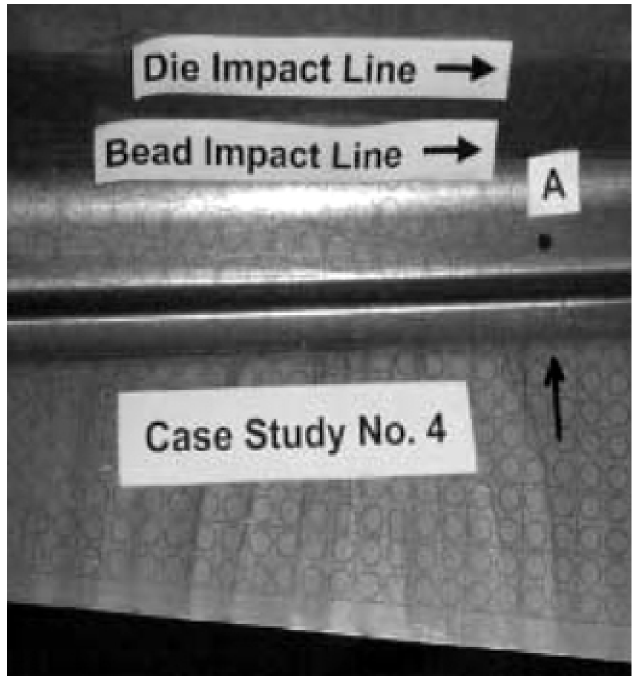

Figure 5. Hood outer panel evaluated after one-year of production.

of production, no tears had been encountered. The gridded panel was given to the EFLC team for evaluation.

The BCF was computed to be 22 strain percent, thereby reducing the corrected major strain to 29 strain percent. While the corrected major strain did not fall below the 26 strain percent major strain level required by green zone or the minimum safety margin, the corrected major strain was well below the 36 strain percent failure level. The decision to go ahead with production of the panel was a valid decision based on the procedure developed by this project.

Task 3: Prepare and publish a report describing and justifying the application methodology.

An extensive report, entitled *Enhanced Forming Limit Diagram—Project Team Technology Report*, was prepared to describe the key results from the research report and their conversion to the BCF methodology acceptable to the press shop. The technology report describes in detail a step-by-step procedure for conducting the analysis and an illustrative calculation. Five case studies are described with complete calculation worksheets and discussion of results. Finally, suggested applications and their limits are presented. The complete Technology Report is downloadable from the A/S-P open Web site www.a-sp.org and is listed under the "Enhanced Forming Limit Diagrams" heading.

Task 4: Prepare and publish a training manual for use in press shops.

While the technology report described in Task 3 above could be used in the press shop, that report contained extensive reference to research procedures and results, as well as great detail. The technology report serves the engineering community but would be confusing for press shop application. Therefore, the project was expanded to include preparing and publishing an additional document, entitled *Training Manual—Enhanced FLC Project*. This manual contains only the press shop procedures and suggested applications for the BCF, summary of the five case studies, and all computational work sheets. The complete training manual is downloadable from the A/SP open Web site www.a-sp.org and is listed under the "Enhanced Forming Limit Diagrams" heading.

Task 5: Conduct training seminars on the application of the BCF technology.

A total of seven training seminars were conducted at different locations. In attendance were representatives from the automotive OEMs, steel companies, tool and die shops, and sheet metal forming research groups. A copy of the training manual was given to each attendee. The concept of the BCF was well accepted by the attendees. In many instances, steps to implement the BCF were initiated by various companies.

Summary

Bending and unbending sheet metal through draw beads and/or over a tool radius with a radius to sheet thickness ratio less than 5 can generate significant amounts of strain. Because these forming modes have both large gradients of strain through the sheet thickness and one or more strain reversals, these strains do not reduce subsequent stretching as much as a uniform through-thickness elongation. Therefore, a BCF must be applied to bending and unbending strains before their severity can be assessed by the FLC.

The completion of this project resulted in a technology report and a training manual, both downloadable from the A/SP Web site www.a-sp.org. Both contain the application methodology, five case studies with complete computational work sheets, and suggested press shop applications. To disseminate this information, seven training seminars were conducted.

C. High-Strength Steel Stamping Project

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Contractor: U.S. Automotive Materials Partnership
Contract No.: DE-FC05-02OR22910

Objectives

- Determine how to accurately predict and control the amount of springback and other deviations from the desired stamping geometry for parts made from high-strength steel (HSS) and advanced HSS (AHSS) prior to the construction of the production tooling.
- Identify part designs and manufacturing processes that will reduce springback and other part distortions and recommend them to design and manufacturing engineers.

Approach

- Enhance HSS stamping springback predictability through finite-element analysis (FEA).
- Improve HSS stamping springback control by developing knowledge of part design geometries that affect flange springback and die processes that control springback.

Accomplishments

- Studied the effects of alternate stamping processes on springback reduction.
- Identified processes to control springback, sidewall curl, and panel twist.
- Built and/or modified tooling for stretch-forming processes of AHSS autobody structural components.

- Established that stretch-forming processes are intended to neutralize the residual stresses that cause springback and sidewall curl. Good results have been shown for HSLA 350 and DP 600. The results with DP 780, DP980 and Trip 800 have been less successful due to the inability to achieve a locked metal condition with simple two-bend lock steps. It is expected that a more complex four-bend lock step will provide the desired results with the higher strength materials.
- Discovered another process showing promise, which is the double-pressure pad form and flange die. This process requires a high-pressure hydraulic cushion that can be programmed for various control features. A die with this type of pressure pad has been designed for this project group and is being built for further experimentation with the higher strength steels. Much higher holding pressures are required for the new grades of AHSS than with current materials.
- Controlled springback by modified panel geometry. Effective use of stiffening beads, ribs, and darts is being recommended to product designers. Springback control experiments were conducted using tooling designed to replicate actual production stamping die processes. These experiments confirmed the importance of optimizing part geometry and the stamping process to reduce residual stress, flange springback, and part-to-part variation. Stampings were made with HSS, AHSS, and tailor-welded blanks. Parts were measured and data were recorded and analyzed. Results will be published in hard copy and on the Auto/Steel Partnership (A/SP) Web site.
- Determined that tooling wear is a major concern due to the higher die pressures and the material strength. This project group is working with the Tribology Project Group to find suitable die surface materials and lubricants. Vapor deposition of chromium nitride on cast iron has shown early promise.

Future Direction

- Complete the construction of the new prototype die and programmable hydraulic cushion. This die is designed as a master die set and pressure system that will accept subdie inserts to produce a variety of structural parts and/or stamping processes.
- Continue wear testing of die materials and die surface treatments with the support of the Tribology Group.

Introduction

Owing to the mechanical properties of HSS, the springback after forming and the geometric dimensional control of the stamped parts has been a critical issue in stamping tool construction and in stamping production. Because the actual dimensions of HSS stampings off the tooling are unpredictable with current tools and technology, the average die face remachining may be four to six times normal and result in 2 to 3 months of lost tryout time.

Computer simulation technology has been widely applied in the stamping industry and has been recognized as a common virtual stamping tool to identify formability issues and evaluate solutions before the actual stamping dies are made. Although computer simulation provides accurate prediction for splits and buckles, experience has shown that computer simulation data have not been reliable in predicting the amounts and modes of the springback, twist, or sidewall curl.

Springback and other distortions in HSSs must be controlled by innovative stamping processes that neutralize residual stresses from the metal deformation. These processes will involve some type of stretch forming to give the stamping “shape set.” The work of this project group is to determine the most effective means of researching and applying these processes. Computer simulation is also being analyzed to improve the data input for accurate formability prediction.

Progress Toward Meeting Deliverables

To assess the accuracy of the current forming/springback simulation technology, a full-scale fender rail stamping die was used (see Figure 1). A lockstep was added to the die to provide sidewall stretch. Two different HSS materials, HSLA 50KSI and DP 600, were used to stamp fender rails and the finished panels measured. Optimum stamping die processes inputs were established through comparison of simulation output with actual stamping die results. Springback control experiments were conducted using tooling designed to replicate actual production stamping die processes. These experiments confirmed the importance of optimizing part geometry and the stamping process to reduce residual stress, flange springback, and part-to-part variation. Parts were measured, and data were recorded and analyzed. Results will be published in hard copy and on the A/SP Web site.

Figure 1. Full-scale fender rail stamping die (lower-half).

Project Status

Currently, the project group is focused on building a research master die with subdie inserts (see Figure 2) to produce various automotive structural components by a variety of processes. This master die will have the necessary higher holding pressures and controlled processes required for working the higher strength materials. A programmable hydraulic pressure cushion will be the main component of this system, which will provide the means of stretch forming the metal and controlling springback. This tooling is scheduled for completion in the first quarter of 2004.

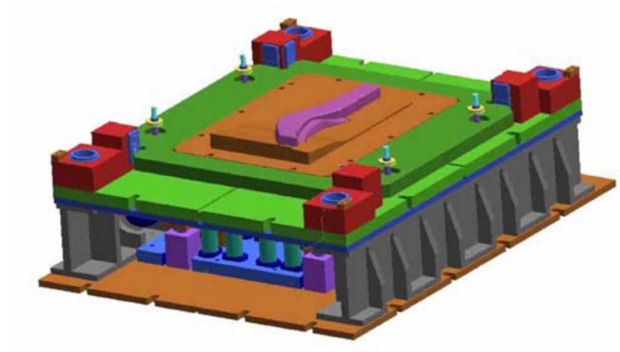

Figure 2. Research master die with subdie inserts.

Future Work

Further attempts at successful stampings of DP 780, DP 980, and TRIP 800 will be conducted on typical automotive underbody structural members with the new tooling and processes. These materials, in lighter gauges than currently employed, will assist the weight reduction goals of other project groups in the A/SP.

D. High-Strength Steel Joining Technologies Project

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Contractor: U.S. Automotive Materials Partnership
Contract No.: DE-FC05-02OR22910

Objective

- Facilitate the increased use of the advanced high-strength steels (AHSSs) in the Auto/Steel Partnership (A/SP) lightweighting projects through the development of weld parameters and weld schedules that will produce quality welds in 12 grades of these advanced steels.

Approach

- Evaluate weld lobe under peel test conditions to determine the optimum welding time and current. Properties such as hardness, tensile shear, metallographic, impact, and fatigue will be evaluated.
- Evaluate weld bonding of three of the AHSSs and compare to straight welded joints. Properties of tensile shear, impact, and fatigue will be considered.
- Document fracture characteristics of these welds and compare to the weld strengths in the development of a standard for partial-thickness fractures.
- Evaluate (Phase II) the weldability of different grades of HSS to each other, and different thicknesses to each other (nine combinations of dual-phase and martensitic steels, 1.5-mm to 2.0-mm thickness, as recommended by the A/SP Lightweight Structures Group). Determine the welding parameters to produce optimum welds and statistically test welds produced at these parameters. Tensile shear, impact and fatigue will be evaluated.

- Evaluate an ongoing project that addresses the effect of tempering welds made with dual-phase and transformation-induced plasticity (TRIP) steels, an AISI/EWI project also in concert with the DOE.
- Secure the various material grades in sufficient quantities to complete the welding and the tests.
- Write the test plan and procedures for the project (Statement of Work).
- Weld coupons and test accordingly.
- Report results.
- Develop a Standard of Acceptance for welds with inner-facial fractures that meet the strength requirements of welds or pull the traditional nugget.

Accomplishments

Weld Lobe Study:

- Established procedure for weld lobe study, testing, and machine characterization.
- Characterized two machines, scissor gun and C gun regarding rigidity and weldability.
- Secured the samples for all 12 materials, at 200 ft^2 each, at Roman Engineering, Inc. Material sheared into coupons and welded for weld lobe study, tensile shear, impact, and fatigue testing.
- Completed weld lobe study on all 12 materials.
- Completed impact tests and microhardness traverse tests on all 12 materials.
- Designed, produced, and tested fatigue test coupons.
- Designed, produced, and tested weld bonded coupons.
- Performed tensile shear on ten material iterations.

EWI/AISI Temper Study:

- Secured five materials for phase 1 work.
- Developed posttempering diagrams.
- Evaluated initial spike tempering.
- Designed process robustness study.

LWFS Weldability Study:

- Ordered materials.
- Developed weld and test program (using weld window).
- Secured welding source.
- Secured prototype build source.
- Received some materials and proceeded to weld coupons.

SWSG MIG/Laser Weld Study:

- Ordered materials.

- Developed test program.
- Selected welding source.

Introduction

The use of AHSS is integral to the steel industry effort to lightweight automotive components while not sacrificing strength or raising costs, an issue with the use of other lightweight materials. Development of welding parameters and the physical testing of the new steels are necessary to qualify these steels for various automotive applications. Extensive work has been completed on the spot welding of mild steels during the Intelligent Resistant Welding Project of the Auto Body Consortium, and various A/SP welding and bonding projects. This study is an in-depth investigation of the weldability and mechanical property improvements using the AHSSs.

Discussion

The Welding Technology Task Force started in about 1990 as an investigative technical committee of the A/SP with the purpose of better understanding production resistance welding processes and increasing electrode life. In about 2000 the Adhesive Bonding group combined with the Welding group to form the Joining Technology Group. When the Lightweighting Structures was formed, all the specific technology groups became "enablers" to the Lightweighting group. The Lightweighting group was charged with the task of using the AHSSs extensively for rails, bumpers, and frames.

Because of strong lightweighting incentives and desire to use the lightest and strongest steels available, coupled with the advancement of dual-phase, complex phase, martensitic and TRIP steels, there is a need to know how to weld the new steels, and how to cope with partial facial fractures.

When the AISI Ultralight Project (ULSAB) showed that considerable weight could be saved by using HSSs, and then AHSSs came on the scene, the Welding committee was given the task of improving the weldability and permitting use of the AHSS in the new designs. When the A/SP was revamped to concentrate on lightweighting issues, Welding was combined with Adhesive Bonding to form the Joining Technologies Group, and Joining became an enabler to the Lightweighting Team.

The projects studied over the years and completed follow:

- Weldability Test Standard Manual (1994–1995)
- Electrode Weld Mechanisms (1995–1997)
  - Hot Dip Galvanized (HDG) Steels (1997)
  - Galvannealed Steels (1996)
  - Finite Modeling of Electrode Tip (1995)
- HSS Weldability (1998–2000)
- IRW Effort (1997–2000)
- Design of Experiments-Coated Steel (1998–2000)

The first project listed, was to develop a qualification procedure that could be accepted by the industry and avoid duplicate or triplicate testing of materials for weldability. This test procedure was developed by the Welding team and accepted by the AWS and SAE under D 8.9 standard. Coupon geometry and electrode shape were evaluated and established in the standard test. Today this is a widely used standard.

One of the early projects was a study of electrode weld mechanisms and electrode wear on both galvanized and galvannealed steels. This study was led by Edison Welding Institute and Michigan Technological University in an effort to study electrode wear mechanisms and increase electrode life. It was found that aluminum content in the

HDG coatings in excess of 0.2% caused a rapid decrease in electrode life. It was also determined that electrode life decreased sharply as expulsion occurred, which was related to excessive current. Truncated cone electrodes also proved to be the best.

One of the studies led by Battelle Institute, was "Finite Modeling of the Electrode tip," adding to the electrode wear mechanism information. Photographic studies during the welding process, by Michigan Technological University, showed graphically what was happening at the electrode tip.

In 1998, investigation of the weldability of the traditional HSSs 50 ksi and over, such as high-strength low-alloy (HSLA), HSS, and Bake Hardenable (BH) was started. A Design of Experiments was proposed and completed using these steels, looking for a way to increase electrode life and to make the process robustness on the production floor. The aspect ratio (a measure of the size and roundness of the weld nugget) proved to be a measure of process robustness. When welds exceeded an aspect ratio of 2.0, the process becomes erratic. In this case the electrode should be redressed and welding continued. The current was also kept to a level just below "weld expulsion," to keep the process in control.

Four welding projects that are enablers to the Lightweight Front Structures Group are

1. Weld lobe study,
2. EWI/AISI temper study,
3. LWFS weldability study, and
4. SWSG MIG/laser weldability.

The **weld lobe study** involves the weldability of 8 different AHSS steels in 13 coating combinations, which may used in AHSS designs. Using two different weld guns (C gun and pedestal gun), and three hold times (16, 22, and 28 cycles), welds were made and peel tested.

Shown below is the materials matrix to be evaluated: All the steel was 1.5 mm thick and welded to itself.

Grade:
High Strength Low Alloy—HSLA HD—1.5 mm
High Strength Low Alloy—HSLA GA
Dual Phase 600—DP-600 GA
Dual Phase 600—DP-600 HDG
Dual Phase 600—DP-600 CR
Dual Phase 980—DP-980 CR
Recovery Annealed 830—RA-830 HDG
Recovery Annealed 830—RA-830 CR
Martensitic 1320—MS-1320 CR
Transformation-Induced Plasticity—TRIP-600 CR
Transformation-Induced Plasticity—TRIP-800 EG

The process of investigation involved:
1. secure materials and shear and weld coupons,
2. determine best schedule for three hold times on both guns at a current below expulsion (peel testing at each level), and
3. perform property tests and chart results.

Making welds along the power curves at 16, 22, and 28 cycles, the parameters that produced 6-mm welds were recorded. Then tested welded coupons were made on this schedule for tensile, impact, hardness, metallographic, and fatigue.

Figure 1 shows the welding curves and resultant welds produced along them.

Figure 2 shows the impact data comparison of the first six steels tested:

Impact test coupons were made and tested on the IRW impact machine developed during the IRW study, and tested at the University of Toledo.

Fatigue tests were made and evaluated by the Fatigue Team of ASP for nine of the material iterations. The Fatigue Team had already tested the mild steel and some of the traditional HSSs as base metal. Figure 3 shows the load amplitude for the various materials using a tensile shear coupon. There is very little difference in all these steels for tensile shear. Cross tension tests showed much more variability. Microhardness tests were made at each level.

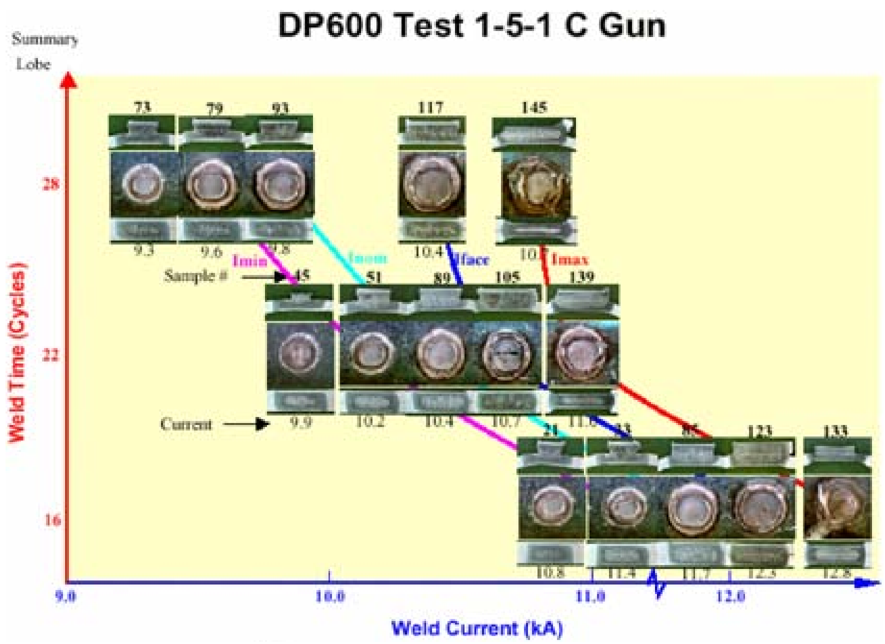

Figure 1. Welding curves and welds produced.

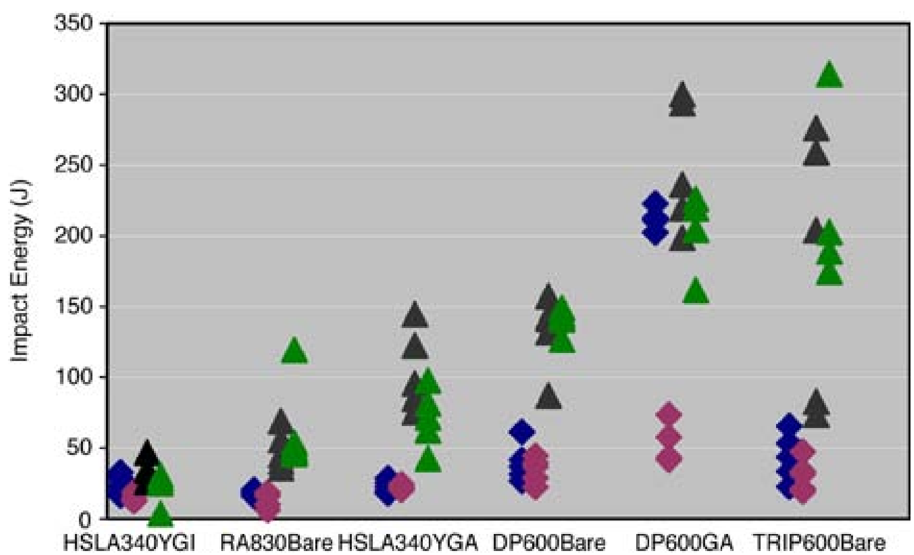

Figure 2. Impact data comparison of first six steels.

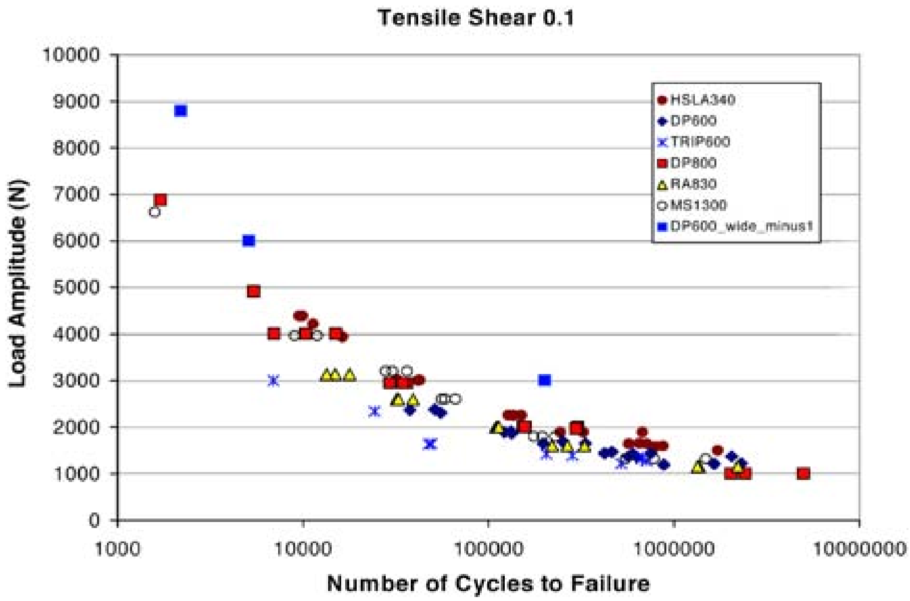

Figure 3. Load amplitude vs cycles to failure.

Involved in this study was the use of weld bonding on three of the materials and comparing test data of weld-only vs weld-bonded. The materials are DP-600 GI, DP-600 GA, and HSLA 340 GI. The results show about a 50% increase in lap-shear tensile for weld bonding over weld only.

An acceptance criteria document in the form of a fracture classification chart, which would discriminate between good and bad welds, was drafted. This is confidential information, not for publication yet.

The **EWI/AISI Temper project** was one where AISI and EWI were cooperating with the DOE to evaluate a fallback position, by welding and posttempering or spike tempering AHSS welds to produce ductile welds and possibly reduce any partial facial fractures. The Partnership assumed the involvement of AISI, and proceeded to evaluate the work and its feasibility to the use of AHSS. Six AHSS materials were compared, with tempering curves developed.

The process here was to

1. secure material, shear and weld;
2. develop tempering diagrams during welding;
3. detail the spike-tempering region; and
4. study for process robustness.

The materials matrix for this project is shown below:

Grade:
Dual Phase—DP-600 1.6 mm to Self
Dual Phase—DP-800 1.0 mm to Self
Dual Phase—DP-980 1.6 mm to Self
TRIP—TRIP 600 1.6 to Self
TRIP—TRIP 800 1.6 to Self
Martensitic—MS-1300 1.0 to Self

The Lightweight Front Structure Project

A weldability program was intended to evaluate nine particular AHSS for use as the Lightweight Front Structures Project (8.I). In this case, a weld window would be determined for each material or combination, and the “sweet spot” of optimum welds was chosen. A statistical number of welds were made using these parameters, with testing for tensile strength, impact, hardness, and fatigue for each iteration.

The materials matrix for the Lightweight Front Structures Group (resistance welding):

Grade:
DP-980 1.0 to Self
DP-800 1.0 to Self

DP-800 1.2 to Self
DP-800 1.4 to Self
DP-800 1.4 to DP-800 2.0
DP-800 1.2 to DP-800 2.0
DP-800 1.4 to DP-800 1.4 to DP-800 2.0 (triplicate)

The test process would be to
1. secure materials and shear and weld coupons,
2. using a weld window, determine best weld schedule,
3. make 25 samples for statistical test, and
4. perform tensile shear, impact, hardness, and fatigue.

Several new materials were suggested as designs progressed to make lightweight rails; consequently, this added to the program. Several tests have been completed for the martensitic steels and DP 800.

SWSG MIG\Laser Project

The latest project to be incorporated is the weldability of AHSS using GMAW welds and laser welds and modified MIG and Laser processes. Obviously, this is a different joining process than RSW, but it is used extensively in frame, bumper, and rail construction.

Many of the same AHSS materials will be evaluated by these fusion-welding processes. The test process for this project will be
1. secure materials and shear coupons,
2. weld coupons by various MIG and laser processes,
3. test by bend test and tensile, and
4. record results and use parameters to weld prototype parts.

These four welding projects will be contributing to the knowledge base to understand and improve weldability, and the effect upon the properties of the welded coupons and the welded assemblies. Weldability is characterized by the welding schedules and subsequent use of these schedules to make prototype parts like rails, bumpers, and frames.

By determining proper weld schedules for each material and stack-up, a starting point to weld prototype parts and establish schedules for the production floor has been determined. The welding source will also be closely involved with the Prototype builder to make parts as early as March 1, 2004. This database of weld schedules for many combinations, gives the designer a wider choice for material combinations to feed into his design models.

The deliverables from these four projects will include
1. welding schedules for a variety of material combinations,
2. welding validation on prototype parts,
3. property values on a variety of welded combinations, and
4. acceptance criteria for the production floor.

In the next few months, both laboratory and prototype build data are forthcoming. Most of these welding efforts will conclude this year, with the exception of some of the MIG and laser work due to funding restraints.

E. Sheet Steel Fatigue Characterization

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Contractor: U.S. Automotive Materials Partnership
Contract No.: DE-FC05-02OR22910

Objectives

- Compile the test data generated in the previous phases of the program into a user-friendly database so that it can be used in all phases of design and structural analysis of sheet steel vehicle bodies.
- Investigate the fatigue life of joints formed by spot welding and weld bonding (a combination of welding and adhesive bonding).
- Explore the parameters for testing metal inert gas (MIG) and laser-welded joints.

Approach

- Investigate spot welding, a fusion process in which the metal being joined is melted and re-solidified to form an alloy with a distinctly different microstructure from that of the metal(s) that are joined. In addition, the weld nugget, or button, may contain discontinuities, which can become sites at which fatigue cracks form. The amount and type of discontinuities are affected to a considerable extent by the welding process. The microstructures of the joined metals are also refined in the area adjacent to the weld, which is known as the heat affected zone (HAZ).
- Investigate adhesive bonding that introduces an entirely different material into the load path, which must adhere to the metals being joined and resist fatigue failure at the areas of contact and within the adhesive.
- Investigate these previously unknown, or at best little known, factors that are expected to improve durability and facilitate modeling and simulation. Therefore, the testing was conducted on a variety of steel grades and coatings.

Accomplishments

- Defined parameters of the database and engaged a contractor to perform the work. The database has been constructed and is being evaluated by team members. Work is expected to be complete in early 2004.
- Selected 22 combinations of steel grade and coating. Of the combinations, 17 were spot welded, with 8 completed and 9 in process. Two of the combinations were weld bonded, and both have been completed. Three of the combinations were bonded, with all three in process.
- Contacted several consultants and invited them to present proposals for fatigue testing MIG welds.

Introduction

In the era when vehicle mass was not a drawback and, in fact, was sometimes considered an advantage, the primary concern in body design was rigidity. More recently, the need to reduce body mass to comply with mandated corporate average fuel economy (CAFE) while improving the levels of occupant protection in a crash caused design engineers to reexamine design procedures and materials. High-strength steels, judiciously selected and applied, emerged as potential low-cost (compared with aluminum and plastics), reliable materials for meeting these mandates. As structural components are optimized and thinner gauge, higher strength materials are assessed, fatigue life of the component and the areas where loads are transferred become considerations. To assess the performance of a component in the design phase, the fatigue characteristics of the base material and the areas where loads are transferred must be known. This project has completed a significant amount of testing of various grades of steel and is currently addressing joining methods most commonly used in vehicle bodies made from sheet steel.

Details

The three participating auto companies have been investigating the fatigue characteristics of spot welds, but there remains a need for a joint effort to evaluate the fatigue characteristics of spot welded and weld bonded joints. The effort began in the 2002 fiscal year with presentations by key researchers on the current state of the work at DaimlerChrysler Corporation, Ford Motor Company, and General Motors Corporation. Based on these presentations, the Sheet Steel Fatigue Project Team was able to develop parameters for a test program that would produce results beneficial to all three companies. Early in the planning, the Auto/Steel Partnership (A/SP) Joining Technologies Team was consulted, and it was agreed that Joining Technologies would prepare the samples to be tested. This interaction ensured that the samples would be joined using procedures that were properly controlled and in adherence to the best current practices in sheet metal joining.

The following test parameters were developed and agreed on in the planning stage:

1. There will be two modes of testing: tensile shear and coach peel.
2. Weld fatigue performance is independent of metal thickness for mild steels and high-strength low-alloy (HSLA) grades; therefore, tests on these grades will utilize only one metal thickness (1.6 mm).
3. Because no such data are yet available for advanced HSS, several grades in this class will be tested at two thicknesses (1.6 mm and 0.7 mm).
4. Testing will be done at two R ratios: 0.1 and 0.3. R is the stress ratio, defined as the ratio of the minimum stress to the maximum stress in the test cycle.

Maximum and minimum values are algebraic, with tension designated as positive and compression negative.
5. Eight steel grades will be tested.
6. Testing will include both spot welded and weld bonded joints.

Eight testing laboratories known to have capabilities in this type of testing were invited to submit proposals. Two were selected to perform the work: The University of Missouri in Columbia, Missouri, and Westmoreland Mechanical Testing and Research, Inc. in Youngstown, Pennsylvania.

As the testing progressed, and results were analyzed, the following tests were added for comparison purposes.

1. Testing at specified R ratios means that the maximum and minimum loads are constant throughout the test. This process is valuable for establishing baseline data. However, in the real world, loads can be expected to vary. For this reason, two sets of spectrum loading tests, run at predetermined load variations, were scheduled.
2. Two tests are in progress on samples with a different welding schedule that produced a smaller weld button.
3. Three tests were scheduled with samples joined by adhesive bonding only.
4. At the request of the Joining Technologies Team, three tests were scheduled using wide samples (125 mm vs the standard 38 mm). The wider samples minimize twisting of the weld under load.

Preliminary analysis of results received to date indicate that the fatigue performance of a spot weld is independent of the materials being welded. This is thought to be due to the melting and resolidifying processes (see Approach, above), which make material properties, coating, and welding paremeters insignificant contributors to fatigue performance.

Continuing Work

During the next 6 months, raw data received from the testing sources will be processed into a format useful for engineering analysis and compiled into a Web-enabled database. The anticipated date for uploading the database to the Web is April 30, 2004.

F. Strain Rate Characterization

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Contractor: U.S. Automotive Materials Partnership
Contract No.: DE-FC05-95OR22363

Objectives

- Develop new experimental setups for characterization of crashworthiness and strain rate sensitivity of high-strength steels (HSSs).
- Replicate impact conditions that occur in automotive impact by simpler and more manageable experiments.

Accomplishments

- Developed experimental setup procedures for new crashworthiness characterization test based on parallel-plates buckling (procedure was developed at the University of Dayton Research Institute).
- Developed and conducted constant-velocity crash experiments on circular tubes made of dual-phase (DP) and transformation-induced plasticity (TRIP) steels.

Future Direction

- Conduct and analyze crush experiments on coupon level (parallel-plate impact test).
- Develop experiments for characterizing strain and strain rate history in tubular components (circular and rectangular tube crush tests).

- Provide high-quality data for material and finite-element method (FEM) modeling development.

Introduction

Crashworthiness characterization of HSS[1] requires testing of materials and structures under increased strain rates, large plastic strains, and large displacements that are characteristic of actual impact events. Aside from providing a physically quantitative measure of crashworthiness, the experiments also provide benchmarks for verification of FEM models that are used for automotive design and analysis. Typical crashworthiness experiments involve crushing of tubular objects, such as circular or rectangular tubes.[2] Due to a combination of relatively high velocities and force levels required for progressive crushing, the experiments are usually conducted in inertia-based equipment, such as drop towers or impact sleds. For example, in a drop tower the drop height and the drop mass can be adjusted to generate desired crush force and length. However, there are practical limits on the mass and the velocity that can be used in a drop tower. The kinetic energy of the impact must be such that it can be expended in the deformation of the specimen and the safety restraints in order not to damage the testing equipment. Vibrations of the falling mass are practically impossible to eliminate, and the lateral forces are not easily measured, nor controlled. The velocity of impact cannot be kept constant and gradually reduces from the onset of impact.

The objective of this project is to develop and conduct coupon- and component-level experiments for characterization of crashworthiness of HSS. The project will also provide high-quality data for development of material and structural FEM models, and, therefore, enable more accurate modeling and design of lightweight crashworthy vehicles.

Design of Experiments

Parallel-Plate Impact Test

A new coupon-level test based on parallel-plate drop tower test by Tam and Calladine[3] has been developed for the servo-hydraulic testing machine. The University of Dayton Research Institute (UDRI) was contracted to perform high-strain-rate double-hinge buckling tests as part of Auto/Steel Partnership (A/SP) work to develop structures for the automotive industry that will improve passenger safety in crashes. Results from drop tower tests were used to develop a model of energy absorption. The results from the test will be used for characterization of material under impact and bending. The tests are currently under way at the UDRI.

The test is developed with the objective to replicate deformation history of automotive structures made of polygonal tubular components that occurs during impact. The simplicity of the specimen allows for analytical extraction of data and simple correlation with the FEM experiments. The instrumentation includes strain gages and a high-speed camera that will be used to correlate the measurements. The initial fixture design with the specimen and the specimen after the test are shown in Figures 1 and 2.

Due to the problems with obtaining symmetric deformation that is crucial for interpreting the data from the experiments, several modifications were made to the preparation of the specimens and the fixture. Current specimen design is shown in Figure 3.

Up to eight strain gages are used to record strain history for a test. Gages are arranged as seen in Figure 4, with gages 4, 5, and 6 placed back-to-back with 1, 2, and 3. If desired, the location of gage 8 can be changed after the first few tests. The strain

Figure 1. Double-plate test fixture.

Figure 2. Double-plate specimen after impact.

Figure 3. Specimen design.

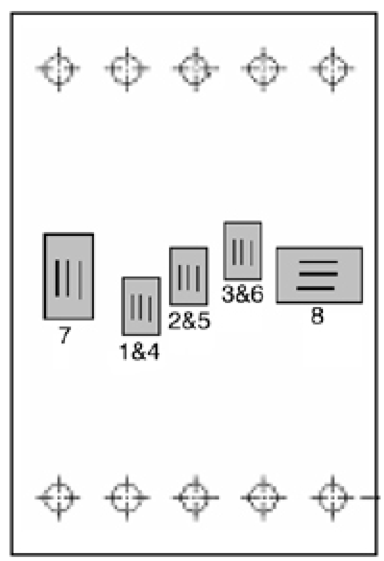

Figure 4. Strain gage location.

gage equipment will be calibrated to record up to 10% strain, or 20% strain, as appropriate. Some of the gages may be set to record a smaller scale on some of the tests to capture the onset of yielding. Strain gages are applied in accordance with procedures published by the manufacturer.

Results from the latest successful test setup are shown in Figure 5. The increasing numbers below the photographs denote the relative time sequence.

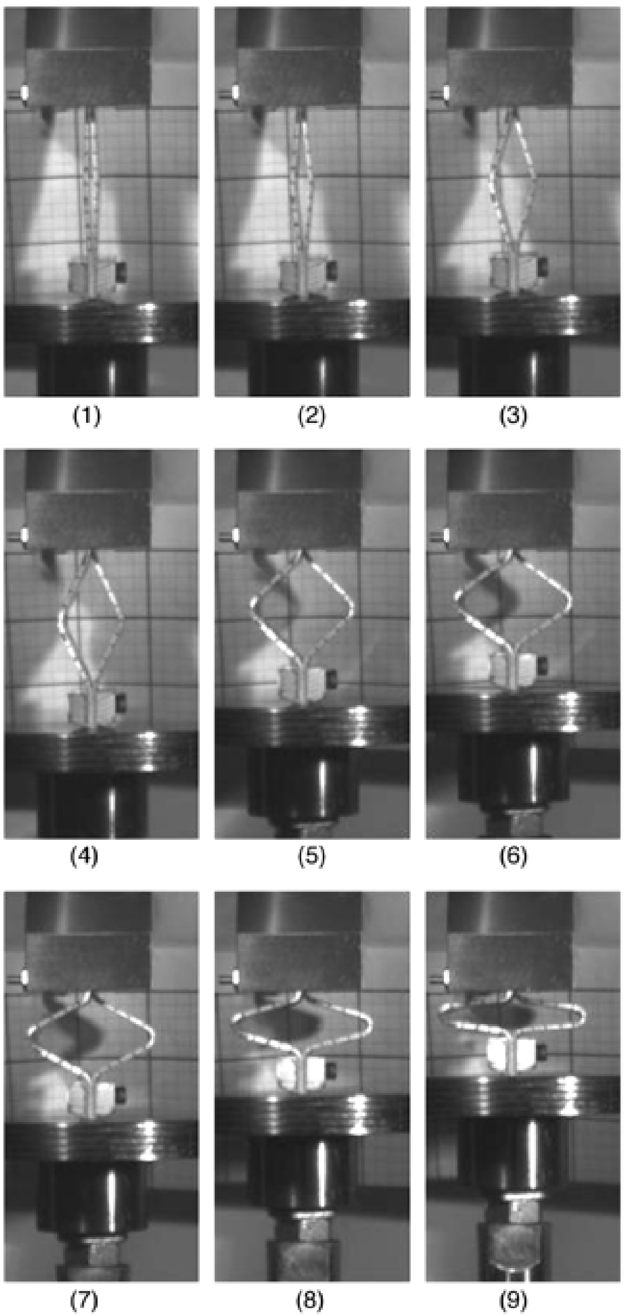

Figure 5. Double-plate test.

Data from the test are used to develop information about material rate sensitivity and deformation during early impact and formation of plastic hinges. The data are also used for correlation with and modification of the computational FEM models.

Tube Crush Experiments

To improve experimental investigations of the material and structural behavior for automotive impact, the Oak Ridge National Laboratory (ORNL) and the ACC of USCAR have developed a new integrated virtual and physical test system for hydraulic, high-force, high-velocity crashworthiness experiments of automotive materials and structures. This unique system, the test machine for automotive crashworthiness (TMAC), permits controlled, progressive crush experiments at programmable velocity profiles and high-force levels. More details about the TMAC system can be found on http://www.ntrc.org and in 7.C.

The tube crush experiments were conducted at the National Transportation Research Center user facility in Oak Ridge, Tennessee. The TMAC system is shown in Figure 6.

The ability to control displacement (velocity) and large lateral stiffness of the machine allows for strain history measurements[4] that are not practical in drop tower equipment. The test setups have been developed and will be reported in forthcoming publications. The current document deals only with global measures, such as loads and displacements and their comparison with the simulations.

The test specimens were provided by the U.S. Steel Corporation. Two materials were tested:

(a) DP600 600-MPa steel, and
(b) TRIP 600-MPa steel

Tube diameter was 70 mm (2.75 in.). The tubes were made by the ERW method. Tube

Figure 6. Test machine for automotive crashworthiness.

thickness was 1.6 mm in both cases. Basic material properties along the circumference of the tubes are shown in Table 1.

Table 1. Material properties

Test direction	Location (0° weld)	Yield (MPa)	Tensile (MPa)	Total elongation (50 mm)
Dual-phase 600 1.6 mm				
L	0	573	666	15.5
L	90	453	635	23.8
L	180	459	625	22.2
T	0	419	638	18.8
T	180	410	649	24.0
Trip 600 1.6 mm				
L	0	676	795	17.5
L	90	465	640	30.1
L	180	480	635	31.4
T	0	466	648	16.1
T	180	414	638	30.0

In the table, L and T denote directions along the length and circumference of the tube, respectively. Test tubes were cut to length of 0.254 m (10 in.). The base of the tube was restrained by a steel insert mounted on the supporting plate of the machine. The drawing of the insert is shown in Figure 7.

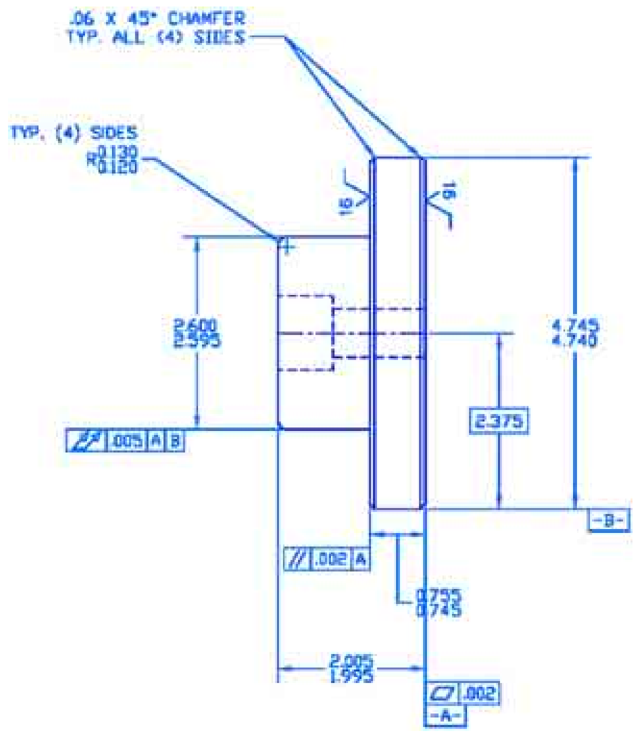

Figure 7. Tube insert.

Because of the high imperfection sensitivity of circular tubes[5,6] it was necessary to incorporate crush initiators into the tubes in order to generate a repeated folding mode. The various modes and magnitudes of imperfections were considered using FEM models to determine the controlling factors for tube fold formation. It was determined that the tube top height imperfection (or equivalently the loading plate angle) has dominant influence on tube crush for the practical imperfection ranges already present in the tubes. This finding was in agreement with experiments reported in the literature.[7] Therefore, the tubes were cut at an angle of 2° to initiate folding at the predetermined location and mounted in the equipment as shown in Figure 8.

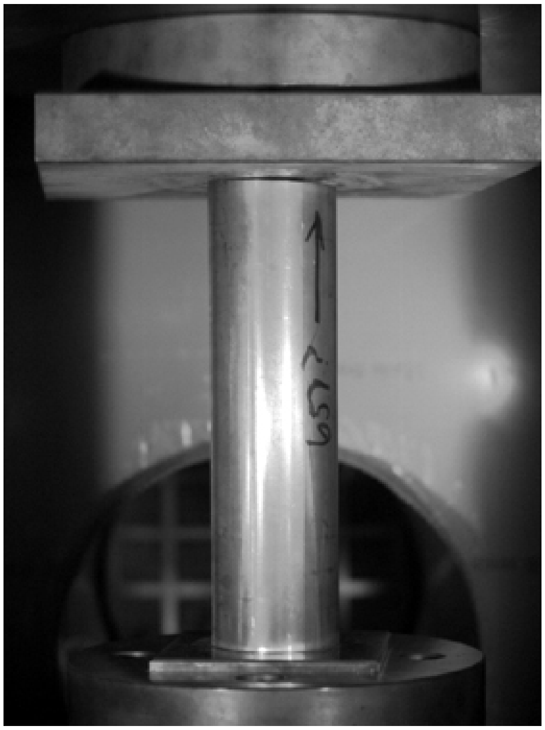

Figure 8. Experimental setup and initial tube imperfection.

Several loading velocities were considered. The tubes were crushed under effectively quasi-static mode, and under constant actuator velocities of 0.6 m/s, 1 m/s, 2 m/s, 4 m/s and 6 m/s. The tests were recorded with a high-speed camera. Typical sequence of deformations for crush velocity of 2 m/s and DP steel is shown in Figure 9.

The tube force was measured by a set of load cells and a load washer. The data from load sensors, displacement trace, and high-speed camera are synchronized and together provide comprehensive information about the progressive crush, and crashworthiness. This information can be taken advantage of for developing FEM modeling guidelines because we can now easily compare displacements, collapse modes and forces between the models and experiments. The ongoing research involves investigations of different measurement techniques in crashworthiness characterization.

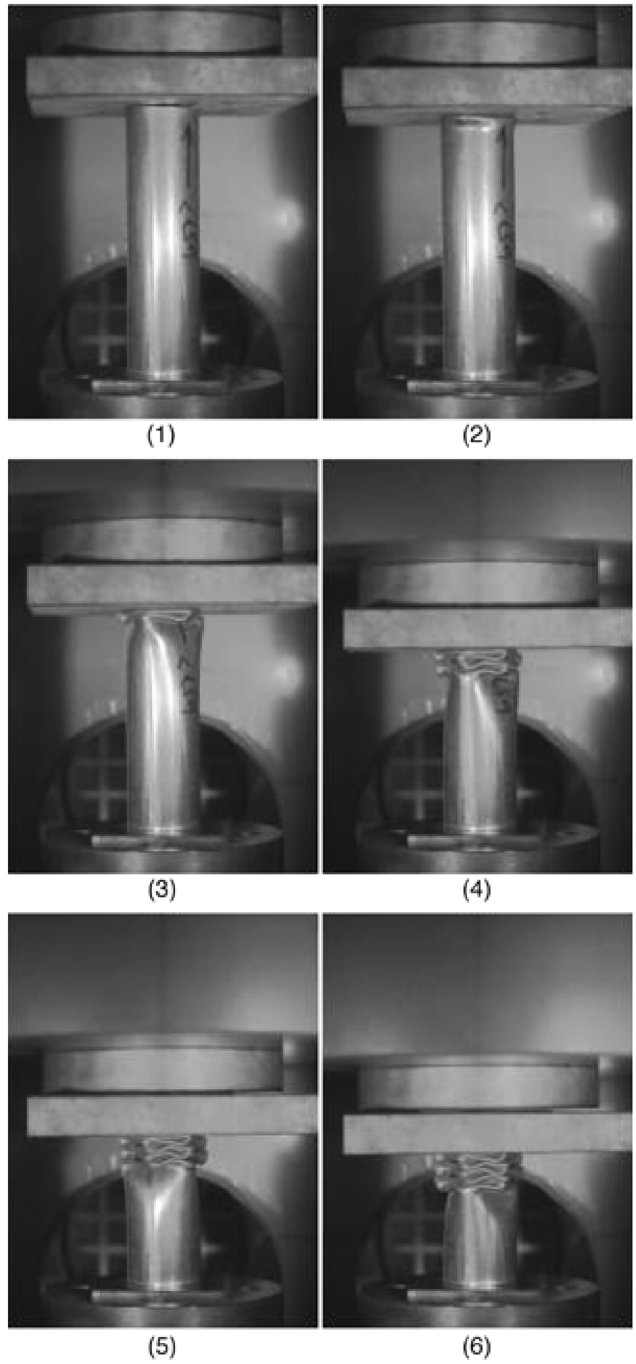

Figure 9. Crush sequence for 2-m/s loading velocity.

Conclusions

Two new experimental setups have been developed for characterization of crashworthiness of HSS. The experiments are based on hydraulic-based testing systems. The systems provide unique tightly controlled testing environments for structural and material characterization. The experimental data are also used for validation and evaluation of modeling approaches, and for development of modeling guidelines for HSS materials and structures under impact loads.

Acknowledgments

The tubes for experiments were donated by the U.S. Steel Corporation. The support of Auto/Steel Partnership Strain Rate Characterization Team is acknowledged.

Future Work

The future work on the project will focus on four topics:

1. Conducting parallel-plate experiments for HSS under three loading speeds.
2. Conducting circular tube crush experiments in TMAC.
3. Measurement of strain and strain rate histories in parallel-plate and tube crush experiments.
4. Development of experimental setup for crushing of rectangular tubes in TMAC.

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G. Advanced High-Strength Steel Tailor-Welded Blank Project

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Objective

- Investigate the manufacturability and formability of high-strength steel (HSS) and advanced high-strength steel (AHSS) tailor-welded blanks.
- Demonstrate that these products can be used to produce automotive components of significantly lower mass. The application of high-strength low-alloy (HSLA) steels and advanced high-strength steels (AHSS) offer the potential for further weight reduction. However, uncertainty exists regarding the weld processes for these products and the resultant ductility of the weld and heat-affected zone. Develop manufacturing techniques and validate to assure reliable, high-volume HSS and AHSS tailor-welded blanks.

Accomplishments

- Fatigue tested laser welds in AHSS tailor-welded blanks (see Figures 1–3). DP 600-MPa and DP 800-MPa material tests have been completed (see Table 1).
- Defined some product design and manufacturing process modifications for control of springback and side-wall curl on tailor-welded blank stampings of different strengths.
- Evaluated benefits of hybrid laser/arc welding processes for AHSS tailor-welded blanks.

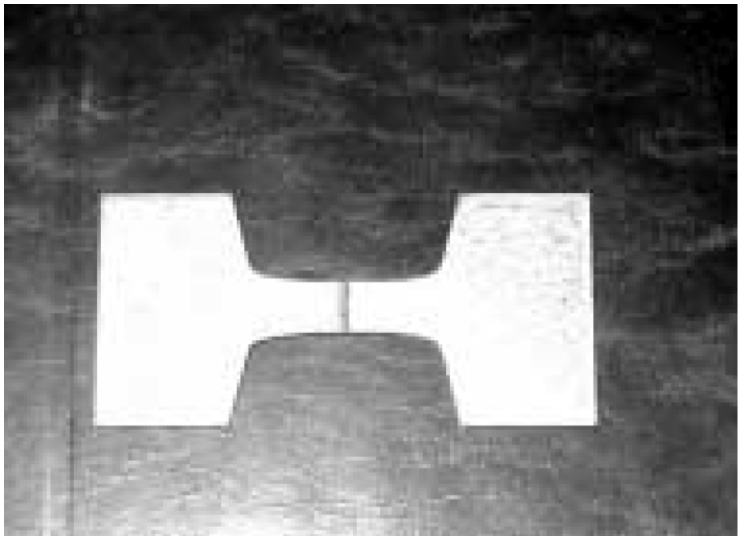

Figure 1. Tailor-welded blank fatigue test specimen.

Figure 2. Fatigue test specimen mounted in test machine grips with an antirotation guide.

Figure 3. A test specimen mounted in the MTS test machine with an antibuckling guide.

Table 1. Tailor-welded blank combinations for tension-compression fatigue tests

DQ 1.6 mm to DP 800 1.2 mm	T-C	Laser
DQ 1.6 mm to DP 600 1.2 mm	T-C	Laser
DP 800 1.6 mm to DP 800 1.2 mm	T-C	Laser
DP 600 1.5 mm to DP 600 1.2 mm	T-C	Laser
DP 600 1.5 mm to DP 800 1.2 mm	T-C	Laser
DP 800 1.6 mm to DP 600 1.2 mm	T-C	Laser
DP 800 1.6 mm to DP 800 1.2 mm	T-C	Laser
DP 600 1.2 mm to DP 600 1.2 mm	T-C	Laser
DP 600 1.2 mm to DP 600 1.2 mm	T-C	Mash

Future Direction

- Expand the fatigue testing for other HSS grades.
- Continue evaluation of hybrid laser processes as well as formability and fatigue testing of test specimens from these processes.
- Continue to work on the control of springback and other distortions resulting from residual stresses in tailor-welded blanks stampings made with materials of different tensile strengths.

Introduction

Tailor-welded blanks have gained acceptance in the automotive industry as a means of part integration or elimination, thereby simultaneously reducing tooling cost and weight. The application of HSLA steel and AHSS, such as dual-phase and TRIP steel, offer the potential for further weight reduction. Optimum weld processes for the high-strength tailored blanks and the resultant ductility of the weld and heat-affected zone must be validated to assure reliable, high-volume HSS and AHSS tailor-welded blanks.

The project group intends to demonstrate that AHSS tailor-welded blanks can be used to produce automotive structural components of significantly lower mass.

Progress Toward Meeting Deliverables

Fatigue testing planning was done in conjunction with the Sheet Steel Fatigue Project Group, the Joining Technology Group, and the Lightweight Front End Structures Project. As they defined the materials they would use for tailor-welded blanks in the motor compartment rails, the Tailor Welded Project Group has determined the required fatigue test procedures and has procured quotes for this work. Fatigue testing of Dual Phase 600- and 800-MPa laser-welded specimens has been completed. Specimens were tested for tension-compression fatigue at the University of Waterloo in Ontario, Canada. Reverse bending fatigue testing was done at the University of Illinois at Urbana-Champaign. Although results were favorable in both tests, further testing with a baseline 350-MPa HSS and other AHSS is necessary for good comparative fatigue test data. More of these specimens will be tested in the near future.

Hybrid laser/arc welded processes for possible improvement of the weld structure were evaluated at Fraunhofer USA in Plymouth, Michigan. Test specimens were produced to further evaluate fatigue, formability, and physical characteristics of this type of weld.

Springback control for tailor-welded blanks of different strength levels is being addressed by manufacturing process and product design modifications. The work to study the effect of these modifications on springback on tailor-welded blanks of different strength levels has been conducted at Ronart Industries in Detroit, Michigan. Recommended modifications have been provided to the automotive group members for future AHSS product design guidelines.

Project Status

The project is currently focused on improving the weld characteristics of AHSS tailor-welded blanks to assure reliable formability and fatigue properties. Laser-welded and hybrid/laser test specimens are being evaluated and the results documented by Fraunhofer USA for reference by automotive product and manufacturing engineers.

Future Work

In addition to planned fatigue testing and evaluation of alternate joining processes for tailor-welded blanks, the project group will keep product designers and manufacturing engineers in the automotive community appraised of innovative applications of this process at domestic as well as at foreign manufacturers.

H. Tribology

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Contractor: U.S. Automotive Materials Partnership
Contract No.: DE-FC05-02OR22910

Objectives

- Conduct stamping simulation tests to study the effects of tribological conditions on the stamping performance of Advanced High Strength Steels (AHSS). Stamping performance in this project is defined as minimizing die wear and maximizing dimensional stability. The understanding of the contribution of lubricants to errors in springback prediction when using finite-element analysis (FEA) will also improve dimensional performance.
- Include these ultimate benefits:
  - Improve test procedure to simulate springback and die wear.
  - Improve control of springback and die wear.
  - Optimize lubricant/die combinations for AHSS.
  - Maintain common lubricants between automotive companies and steel suppliers.
  - Conduct a study to examine wear rates of different die materials.

Approach

- Compare the die wear rate with various HSS and lubricants.
- Correlate other process indicators such as restraining force, temperature, and contact area to wear on the draw beads.
- Correlate the data with the friction test results from Phase 1.
- Build on the extended knowledge gained in Phase 1 and Phase 2. Phase 2 established a baseline of wear data from three sheet steel materials, and two lubricants, with one die material.

Accomplishments

- Completed Phase 1 report "Enhanced Stamping Performance of High Strength Steels with Tribology."
- Completed Phase 2 report "Effect of Stroke Length and Penetration on Die Wear."
- Used steel coils of galvanneal-coated AKDQ, HSLA340, and DP600 supplied by partnership companies. The material is used in the wear tests for Phase 3.
- Collected data for the eight test conditions.

Future Direction

- Develop wear rate model to predict die life.
- Gather wear test data to substantiate model.
- Correlate model with production data as AHSSs come into production.

Introduction

Historically, lubricants are used in forming sheet metal stamping to reduce friction, improve formability, minimize die wear, and provide corrosion protection. The projected increase in the use of AHSSs places a greater emphasis on understanding the process parameters associated with die wear such as heat buildup and die scoring and dimensional stability caused by springback variation. The contribution of interfacial friction to springback variation is not known. AHSSs may require different lubricant and/or die materials to minimize the friction and die wear.

In an attempt to reduce weight, automotive manufacturers are using thinner, higher strength steel panels. Several issues are associated with stamping parts from these steels. The springback of HSS panels results in reduced process capability and greater variations in the vehicle assembly. The higher strength of the steels means that dies will be subjected to higher contact pressure and greater wear. Wear in the draw beads will affect the restraining force and will result in greater variation as well as down time for repairs.

This project will examine how springback and die wear are affected by lubricant and die material with AHSSs. The test simulates the forming of several thousand parts. Changes in process conditions and physical wear on the die are evaluated.

Tribology tests are used to collect data and measure responses such as friction, or restraining force, temperature, contact area, springback, and wear. These responses are related to actual stamping practices, an important step in quantifying the problem and implementing possible solutions.

Background

Phase 1 of this study examined how springback and wear are affected by lubricant and die material with AHSSs. The results presented here outline the results of testing in Phase 1 of the study.

Tribology tests were used to collect data and measure responses such as friction (for restraining force), temperature, contact area, springback, and wear. These responses can be related to actual stamping practices, an important step in quantifying the problem and implementing possible solutions.

Some of the most significant findings included

- significant increase in springback and part temperature with HSSs,
- large difference in friction and wear with dry film lubricants, and

- significant effect on friction and wear from choice of sheet coating.

The broad scope of this study examines the effect of lubricants and die material on formability and die life with coated and AHSSs. In Phase 1, bench tests were used to compare friction and springback results with a broad range of lubricants, die materials, and sheet steels. The data from these tests provided limited information on die wear in production of metal stampings. Because die wear is difficult to measure without extended testing, a modified drawbead tester was developed and constructed and has shown to be effective in producing measurable die wear over thousands of strokes.

Phase 2 studied the effects of bead penetration and stroke length on die wear in the newly developed die wear test. The materials selected for phase 2 were originally intended to be AKDQ, HSLA, and DP600. However, availability of the latter two materials delayed the project to the point where it was decided to use the available material (AKDQ-45/45 galvanneal) as a baseline.

Six coils of material were run through the die wear test (DWT), using three bead penetrations and two stroke lengths. Because coil length was constant, the different stroke length meant that different numbers of strokes were run for each stroke length. The short stroke (50 mm) resulted in 16,000 strokes per coil, while the long stroke (100 mm) resulted in 8,000 strokes per coil. Wear was quantified by weight loss measurements. The large amount of material sliding over the die meant that even under the lowest wear condition weight loss was significant. The 60% and 80% penetration showed similar weight loss trends, that is, higher weight loss with the long stroke length and fewer strokes. Conversely, the 100% penetration showed more weight loss with the greater number of strokes and short stroke length.

These trends were attributed to contact phenomena, which are highly dependent on penetration. The lowest penetration had a single band of wear on the entry side of the bead. With 80% there were two bands of wear, entry and exit. And with the 100% penetration there was a continuous, less severe, band of wear from entry to exit. The concentrated wear with 60 and 80% penetration means that boundary contact is predominant and the lubricant is less effective with long sliding distances. The distributed contact with the 100% penetration allowed lubricant to become entrapped thereby providing protection on the longer strokes.

Continuously measured force and temperature data indicated that temperature and force increase linearly with penetration. It was also found that temperature increased with the number of strokes (after an initial, unexplained, decrease with 60% penetration).

Phase 1 findings show that temperature and pull force will become more important factors with HSLA and DP600 AHSSs. These materials will be studied in the next phase of die wear testing.

The Phase 2 results and analysis show that stroke length and penetration are powerful factors in die wear and must be carefully controlled in future experimentation. Because wear patterns are dependent on penetration, penetrations should be selected to model production practices rather than laboratory practices (DBS). Similarly stroke length in the future wear testing should be controlled to ensure that test parameters model production. In addition, Phase 2 could have an immediate impact on implementation of AHSS. Because bead wrap decreases with AHSS, the effect on die wear patterns and subsequent die wear may be the same as reducing penetration.

Die Wear Test Procedure

This test is a modification of the DBS using coil-fed continuous sheet strip (see Figure 1). The concept of pulling continuous strip through drawbeads to measure wear had been considered by Dr. John Schey and Greg Dalton as early as 1989. Their first DBS

Figure 1. Die wear test.

design allowed for strip feed. This technique has been used at University of Darmstadt with some success. Die temperature and restraining force are measured throughout the test, while die wear is measured upon completion of the test.

Test Parameters

It is recommended that the following parameters be controlled (fixed or varied):

- Process: speed, lubricant type, lubricant amount, pull length, bead penetration;
- Die: surface finish, material, geometry, temperature; and
- Sheet: thickness, width, surface finish, and coating.

Analysis

The following outputs will be measured in the wear test:

- Restraining force,
- Contact area,
- Temperature,
- Bead wear, and
- Thinning.

Redundant Responses

This analysis includes redundant responses in all tests with the hope of identifying the most effective means (analytically and economically) of evaluating the tribological effect on die wear.

The temperature, change in bead geometry, and restraining force will be reported throughout the test from the male bead. The bead will be examined under optical and scanning electron microscopes to determine wear severity.

The data will be compiled and analyzed for cause and effect using statistical analysis. Where trends appear, statistical significance will be tested.

Experimental Methodology

Variable	**Wear test**
Sheet	AKDQ, HSLA, DP600
Coating	Galvanneal
Die	G3500, G3500—ion nitride, G3500—chromium nitride
Lubricant	Mill oil (1.2–1.6 g/m^2)
Total	8 tests

Test Matrix

Test	**Surface treatment**	**Sheet**
1	Flame hardened	AKDQ
2	Flame hardened*	HSLA
3	Chromium nitride	HSLA
4	Ion nitride	HSLA
5	Flame hardened	DP600
6	Chromium nitride	DP600
7	Ion nitride	DP600
8	Best performer	DP600

*Repeated.

Analysis of data will include statistical analysis of the appropriate test responses.

Test Methodology

TribSys, Inc., will conduct experiments to evaluate die wear on drawbeads under the following conditions:

1. A 2-in.-wide strip will be pulled through a set of three beads. The center bead will be used to evaluate wear.
2. Lubricant is mill applied, and weight is measured during testing.

3. For each condition, 500 m of strip will be pulled through the beads. Wear is evaluated by reduction in volume and temperature. Other measurables such as strip condition, vibration (noise), and forces may be included.
4. Results are analyzed using statistical analysis and subjective methods (scanning electron microscope/surface roughness). Analysis of wear will be presented in a report.

Deliverables

- Statistical analysis of data from experimental matrix: restraining force, temperature, contact area, and die wear.
- Tribological analysis of restraining force, temperature, contact area, die wear results with "hypotheses" on cause and effect.
- Ranking of die treatments from best to worst with respect to antiwear properties.
- Summary report in electronic format presented to the A/SP.

Results and Discussion

The type of wear differed with flame-hardened (FH) and chromium nitrided (CrN) displaying abrasive wear. With abrasive wear, die material is removed as the sheet slides over it under the forming pressure. Abrasive wear leads to die geometry changes that can affect part shape and process control. The CrN showed the least wear with little difference between the HSLA and DP600. The ion nitrided (IN) surface treatment showed signs of adhesive wear. With adhesive wear, the sheet adheres to the die and causes buildup of sheet material on the die surface. This buildup caused sheet surface damage and affected restraining force and part stability.

Die temperatures generally rose until steady state was reached (several hundred parts) after that point temperatures either rose or fell depending on die wear type. With abrasive wear temperatures rose, while with adhesive wear temperatures decreased. The CrN showed lower internal die temperatures and higher strip exit temperatures than the FH dies.

Springback as measured by the curl in the strip was greatest with the higher strength materials (Figure 2) and greatest with lower restraining force (Figure 3). Wear scars were most evident on the center bead at the entry and on the exit bead. Wear differences were visible with the naked eye (see Figure 4).

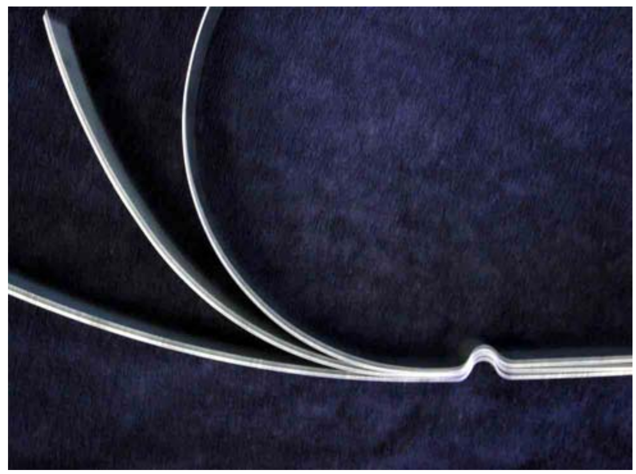

Figure 2. Strip curl of IF, HLSA, DP600 with FH dies.

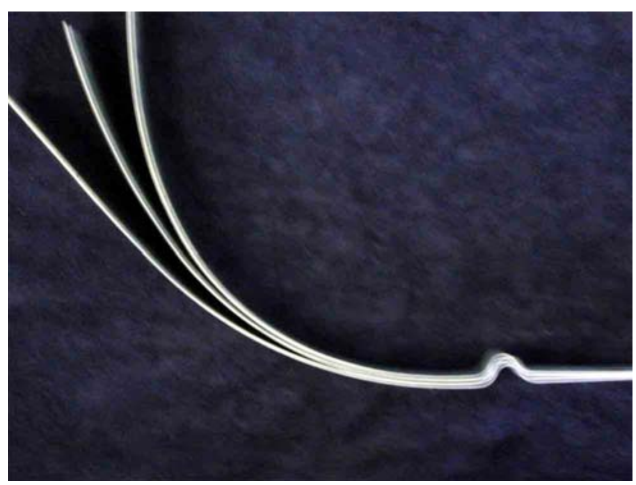

Figure 3. Strip curl with IN, FH, CrN—HSLA sheet.

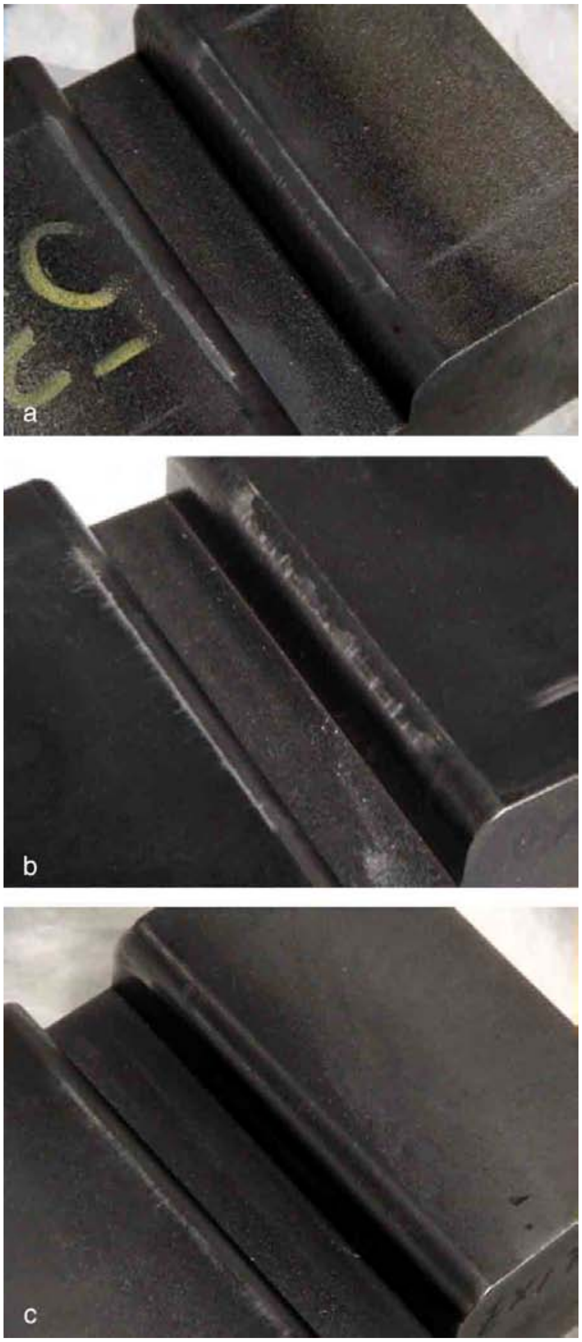

Figure 4. Die wear with (*a*) FH, (*b*) IN, (*c*) CN dies.

Conclusions

1. The die wear test was used to produce continuous die wear data in a coil-fed drawbead arrangement. Preliminary analysis of the data shows that wear type differs with surface treatment and that wear rate increases with increasing sheet strength.
2. As expected from theory and models, springback increases with increasing sheet strength and with reduced retraining force.
3. The CrN surface treatment resisted abrasive wear and showed no signs of adhesive wear with the galvanneal coating.
4. Die temperatures and strip exit temperatures were highly dependent on die surface treatment, die wear, and sheet type.

I. Lightweight Front Structures

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Contractor: U.S. Automotive Materials Partnership
Contract No.: DE-FC05-95OR22910

Objectives

- Benchmark, develop, and document proven solutions that will balance the interaction of material, manufacturing, and performance. The initial phase of the study focused on the automotive front-end system solutions that address high-volume manufacturing and assembly. Example solutions will be manufactured and physical testing will be performed to evaluate the Advanced High Strength Steel (AHSS) designs.
- Use the AHSS solutions to provide choices and consequences that address real world challenges faced in the vehicle development process. A comprehensive knowledge-base design tool will be developed that capitalizes on a set of robust AHSS automotive design guidelines relating choices to consequences.

Approach

- Redesign an existing Front Rail System from a donor vehicle utilizing AHSS (DP800 and above) to save at least 20% mass.
- Manufacture and test the AHSS designed rail system to compare performance with the conventional design it replaces.
- Conduct analytical and physical testing on the original and newly redesigned rail system.
- Draw comparisons and document recommended practices.

Accomplishments

Phase 1 Deliverables

- Completed Phase 1 Engineering Report and posted it on the Auto/Steel Partnership (A/SP) Web site and made available on CD Rom.
- Ensure that related Hyper-view animated crash files are also available on CD ROM.
- Ensure that Windows version of Proteus (knowledge base tool) is available.
- Ensure that a complete “project roll-out” communications package is available.

Phase 2 Deliverables

- Complete preliminary subsystem design.
- Complete competitive benchmarking study.
- Complete rail concept development.
- Complete initial validation of NCAP and IIHS models.
- Complete enhanced crash model report.
- Completed Concept 1 Final Design—Modified baseline vehicle.
- Completed Concept 2 Final Design—Stamped Rail Design.
- Completed Concept 3 Final Design—Hydroform Rail Design.

Future Direction

- Select final design.
- Generate a “response surface.”
- Obtain the final optimized design of rail and bumper.
- Generate CAD data for manufacturing of new rail and bumper designs.
- Develop soft tools for rail and bumper subassemblies.
- Assemble the donor vehicle with new rail and bumper subassemblies.
- Conduct NCAP crash testing of the donor vehicle with new rail and bumper subassemblies.
- Correlate the vehicle crash test data with analytical results.
- Update Proteus (knowledge base tool) with the findings of this project.
- Publish a final report detailing all the findings of this project.
- Develop a “project roll-out” communications package.

Phase 1 Results

In Phase 1 of the project, optimized designs were obtained for two different configurations of the original ultralight steel auto body (ULSAB) vehicle.

The baseline ULSAB vehicle consisted of a front end that could accommodate a 3.1-L V6 engine package and had 195/60 R15 wheels and tires. The baseline ULSAB vehicle also consisted of the same front-end overhang as the original ULSAB vehicle.

The "Best" solution obtained from the knowledge base had the following features: Double 5-star NHTSA/Overall Good IIHS, 12-kg mass reduction compared to the original ULSAB, $69.00 cost reduction, Extensive use of DP800 and DP1000 steels, and mass of structure plus bumper plus cradle 223.3 kg vs 235.3 kg for original ULSAB.

The upgraded ULSAB vehicle consisted of a front end that could accommodate a 3.8-L V6 engine package and had 205/60 R16 wheels and tires. The upgraded ULSAB vehicle had 50 mm less front-end overhang than original ULSAB vehicle. The upgraded vehicle was also 180 kg heavier than original vehicle.

The "Best" solution obtained from the knowledge base had the following features: Double 5-star NHTSA/Overall Good-Acceptable IIHS, 16-kg mass increased compared to original ULSAB, $15.00 cost increase, Extensive use of DP800 and DP1000 steels, and mass of structure plus bumper plus cradle 251.3 kg vs 235.3 kg for original ULSAB.

Because of the increased vehicle weight and geometric compromises, the mass of the upgraded ULSAB vehicle was increased by 28 kg compared to the optimal solution from the baseline ULSAB vehicle. Furthermore, to achieve fully optimized lightweight vehicles, it will be necessary to address the packaging and geometry compromises as well as utilizing advanced materials.

When vehicles become lighter, power trains can become more compact because of lower power demands. Also, if bigger tires and wheels are desired, track width changes should be considered to reduce the impact to the main rails.

Phase 2 Results

The objective of this phase is to benchmark, develop, and document proven solutions that will balance the interaction of material, manufacturing, and performance. The initial phase of the study focused on the automotive front-end system solutions that address high-volume manufacturing and assembly.

The preliminary design of a subsystem was developed to simulate the NCAP performance of a full vehicle finite-element model, in the first 40 ms. The subsystem predicted accurately the full vehicle response in the first 40 ms of the NCAP load case and achieves a 50% reduction in the simulation time. The subsystem achieved the same crush pattern for rail and bumper, as in the full vehicle. The subsystem would assess various rail and bumper concepts in the Lightweight Front-End Structure Project.

A benchmarking study was undertaken to examine rail designs and architectures of competitive vehicles with good NCAP and IIHS performance. The knowledge from this study was very useful in designing AHSS rails for the donor vehicle in Phase II of the Lightweight Front-End Structure Project. A total of 14 competitive vehicles were benchmarked for rail design and architecture.

Various rail concepts were developed for the Phase II donor vehicle by employing AHSS materials. The concepts developed in this study would be further developed into concrete designs and be evaluated for performance, cost, and manufacturability. The most feasible design would be eventually prototyped, assembled into the donor vehicle, and tested for NCAP performance. Three concepts were developed during the course of this study:

Concept 1: Existing Rail Architecture

- Minimum modifications to the current rail design
- Providing design direction
- Filling holes and removing notches
- Reducing flange width
- Tailor-welding DP800T rails
- AHSS materials
- Gauge change

- New bumper: Bumper 3 design from Phase I study

Concept 2: Best Stamped Design

- Improved performance and mass savings
- Hexagonal rails
- Modification of rail curvatures in side view (XZ) and plan (XY) view
- Modification of rail extension
- Possibility of tying rails to rocker and cradle

Concept 3: Best Hydroformed Design

- Alternative to stamped design
- Integration of parts
- Hexagonal/octagonal rails
- Reduction of welding
- Mass reduction by elimination of flanges
- Superior material properties
- Improved crush

New Bumper Design

- Designed to contribute to high-speed crash events
- DP1000T 1.0 mm thick
- Two-piece stamped design
- Feasibility confirmed with bumper supplier
- Common in all the three designs

Regression analysis of the response surfaces obtained from the NCAP DOE Study of Concept 1 resulted in a design with 11 kg (28%) mass reduction and NCAP performance at par with that of the baseline. However, the IIHS performance of the design was inferior to the baseline. The intrusions could be reduced by increasing the gauges appropriately, but it will result in a mass penalty and would not meet the 20% mass reduction target.

A new straighter load path through the existing packaging envelope was developed. This load path would be used by concepts 2 and 3. Requirements to package an engine mount inside the left-hand rail would be eliminated in both the concepts.

A clearance requirement of 10 mm would be set for the worse-case component set. Tailor-welded DP800T rails would be utilized to eliminate reinforcements. Full system optimization would be undertaken to optimize for mass.

Both concepts show potential for the same mass savings of well above the 20% target. Deficiency in stamped design in IIHS was due to lack of development in the kick-down area. Modifications in the stamped design would lead to similar IIHS response as that of the Hydro-Formed concept. Figure 1 shows the three concepts.

Conclusion

One concept will be selected based on the selection criteria set by the project team. A decision will be forthcoming along with a plan and schedule to complete Phase 2 in FY 2004.

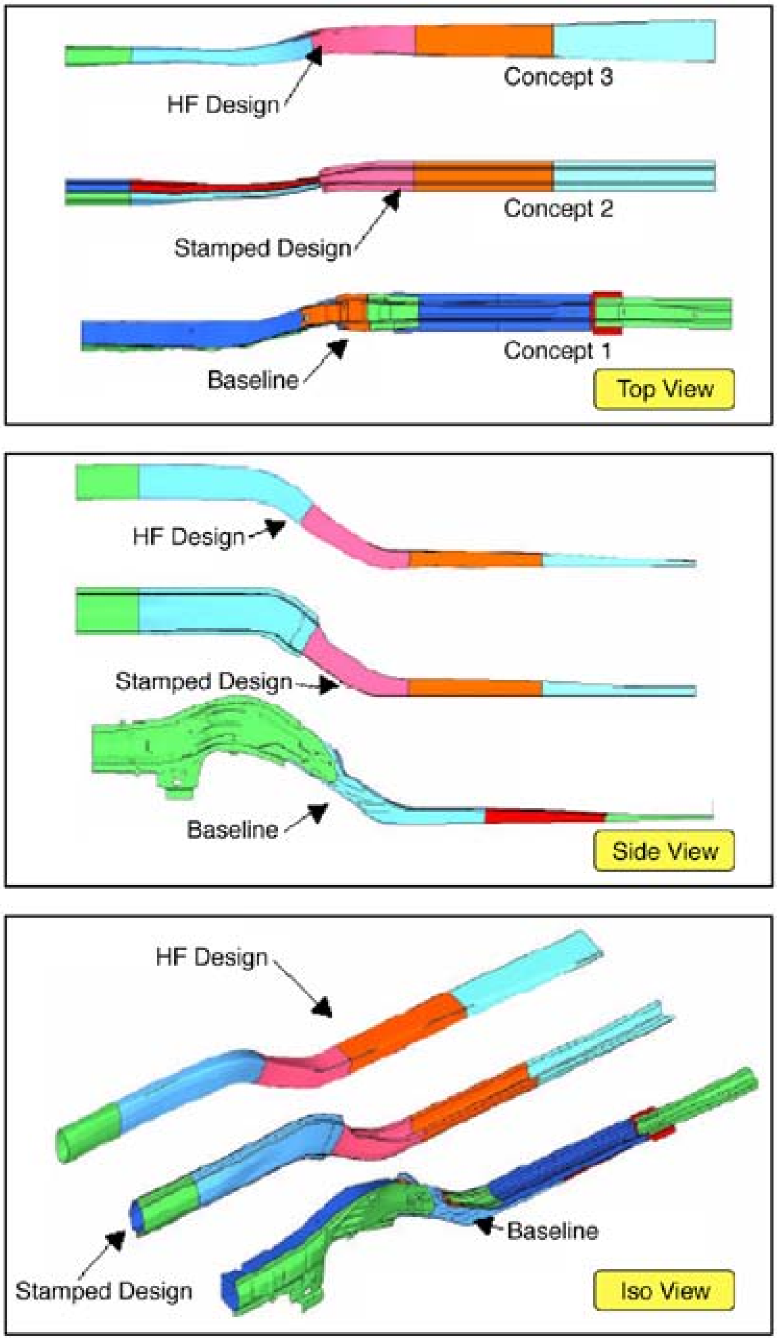

Figure 1. Rail designs: top, side, and isoview.